THE UNIVERSITY OF ALBERTA

THE GEOMORPHOLOGY OF ALLUVIAL FANS NEAR AKLAVIK, N.W.T.

by

© ANDREW BERNARD KEEBLE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

SPRING, 1971

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Geomorphology of Alluvial Fans near Aklavik, N.W.T.", submitted by Andrew Bernard Keeble in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The basic purpose of this study was to determine the nature and areal variation of the principal processes of alluvial fan formation in the Aklavik area. Field work involved the survey of longitudinal fan profiles, the collection of sediment samples from both the fans and mountain mudflows, and the recording of exposures of sedimentary sequences. On return to the laboratory, 170 sediment samples were analysed for grain-size characteristics and a freeze-thaw experiment conducted which indicated that comminution of fan material may take place after depositon, in response to mechanical and chemical weathering.

The Aklavik fans possess gentle slopes with some lobes superimposed on smooth, concave-upward profiles which, together with the absence of deep fanhead incision, suggest that changes in base-level, or periods of mountain uplift, are unlikely to have occurred since deglaciation. A strong inverse relationship was shown to exist between mean fan slope and drainage basin area, suggesting that larger catchment areas produce fans with gentler slopes.

Problems arose during sediment analysis due to the high clay-silt content of samples, producing open-ended grain-size curves. However, evidence from Trask median and

sorting coefficient values, Passega/Bull CM patterns, visual interpretations of grain-size curves, and exposures of sedimentary succession supports the argument that mudflows are active in the fanhead zone, lateral accretion occurs along active channels, and overbank flow deposits much of the sediment in the lower two-thirds of the fan.

Most activity occurs in spring as a result of snowmelt, and for the rest of the year, stream discharge is low. Mudflows are a common feature of drainage basin slopes and are important agents in transporting clay-silt rich material from the upland tundra to the valley floors, where it is subsequently washed out on to the fans.

ACKNOWLEDGEMENTS

The writer wishes to thank Dr. H. J. McPherson, who supervised this thesis, for his aid and guidance during all phases of the study. Thanks are also due to Dr. R. B. Bryan, who originally suggested the topic and gave practical help in the implementation of laboratory techniques, and to Dr. J. Shaw for his many helpful suggestions.

Financial aid for the present study was provided in the form of a grant from the Boreal Institute and an Inter-session Bursary from the University of Alberta. This support is gratefully acknowledged.

The Federal Research Laboratory at Inuvik provided logistical support whilst in the field, and the writer is especially indebted to Richard Hill, John Ostrikh and Bob Hunter for their interested help. The solitude of the wilderness was relieved by the company of Roger Gruben of Tuktoyaktuk, whose willing cheerfulness as a field assistant was invaluable. To the Delta Cafe, Hudson's Bay store, and Nursing Station of Aklavik, the writer extends his thanks for the mental, physical and medical support that they provided during field work.

Thanks must also be given to Jack Chesterman, for his help in the reproduction of maps and photographs, and to Mrs. Vivian Wenger, who typed the final draft of this thesis. I especially wish to thank my wife, Meg, for her continuous support throughout the study.

TABLE OF CONTENTS

Page

Abstract iii

Acknowledgements v

List of Figures viii

List of Tables x

List of Plates xi

Introduction xiii

CHAPTER

I. ALLUVIAL FAN CHARACTERISTICS 1

Fan morphology 1
Process 3
Theories of fan formation 5

II. THE STUDY AREA 10

Location 10
Geology 11
Origin of the Aklavik scarp 12
Isostatic and eustatic change 14
Post-glacial geomorphology 15
Vegetation 16
Soils 17
Climate 19

III. EXPERIMENTAL DESIGN AND RESEARCH TECHNIQUES . . 22

Selection of fans for detailed study 22
Sampling design for fan sediments 23
Field sampling techniques 24
Sample size 24
Surveying techniques 25
Mapping of sedimentary sequences 26
Mechanical analysis of samples 26

CHAPTER PAGE

IV. FAN MORPHOLOGY 28

Fan shape 28
Fan slope 29
Fanhead incision 33
Summary 35

V. SEDIMENT ANALYSIS AND PROCESS DIFFERENTIATION . 36

Visual comparisons of grain-size curves . . . 37
Statistical expression of sediment characteristics 37
CM patterns 40
Areal characteristics of fan sediments . . . 45
Sedimentary sequences 47
Sediment analysis conclusions 48
Hydrologic regime of the Arctic 49
Mudflow activity in the study area 54
Comminution of sediment by freeze-thaw and organic breakdown 60
Summary 66

VI. SUMMARY AND CONCLUSIONS 68

BIBLIOGRAPHY 74

APPENDIX A Sample Locations 81

APPENDIX B Sample and Permafrost Depths 82

APPENDIX C Sample statistics--Median and Trask Sorting Coefficient 84

APPENDIX D Sample statistics--Percentage weight of grain-size classes . . . 86

LIST OF FIGURES

FIGURE FOLLOWING PAGE

1. Location of the study area within the Mackenzie Delta 10
2. Geology of the study area 11
3. Stratigraphy of the Aklavik Range 11
4. Cumulative curves of particle size distribution of crest samples 13
5. Climatic data for Aklavik, 1931-1960 19
6. The study area 22
7. Flow chart for mechanical analysis of sediment samples 26
8. Longitudinal fan profiles 29
9. Relationship between fan slope and drainage basin area 32
10. Grain-size curves--Bear Creek fan 37
11. Grain-size curves--Fault Creek fan 37
12. Grain-size curves--Tundra, Wolf and Willow Creek fans 37
13. Grain-size curves--Mudflows 37
14. CM patterns for study area sediments 42
15. CM pattern locations--Mudflows 44
16. CM pattern locations--PQ segment (lateral accretion deposits) 44
17. CM pattern locations--RS segment (overbank deposits) 44
18. Grain-size isoline maps--Bear Creek fan 46

FIGURE		FOLLOWING PAGE

19. Grain-size isoline maps--Fault Creek fan 46

20. Fourth order trend surface and residuals for clay percentages of Bear Creek fan samples 46

21. Exposures of sedimentary succession 47

22. Borehole profiles from the Aklavik fans 48

LIST OF TABLES

TABLE		PAGE
1.	Correlation matrix of morphological variables . .	30
2.	Mean slopes and drainage basin areas for selected fans	31
3.	Correlation matrix for mean fan slope against drainage basin area	32
4.	Depths of fanhead incision at the apex	33
5.	A sample of mudflow locations and slope angles .	58
6.	Clay-silt percentages produced by freeze-thaw and organic breakdown	63
7.	Comparison of freeze-thaw and organic sample means	65

LIST OF PLATES

PLATE			FOLLOWING PAGE
1:	A.	The study area looking north from Mt. Goodenough	10
	B.	"Stone garlands" on tundra above Bear Creek . . .	10
	C.	Detail of "stone garlands" showing rounded pebbles	10
2:	A.	Valley-in-valley morphology--Fault Creek	14
	B.	Valley-in-valley morphology--Bug Creek	14
	C.	Terrace remnant--Bug Creek	14
3:	A.	Exposed interfluve between Wolf and Willow Creeks	15
	B.	Mass movement lobe above Jimmy Creek	15
	C.	Earth hummock stripes above Fault Creek	15
	D.	Tussocks, hummocks and mud-boils--Tundra Creek .	15
4:		Bear Creek fan	22
5:		Fault Creek fan	22
6:		Sampling transects and survey lines	23
7:	A.	Gravels--Willow Creek fan apex	47
	B.	Gravels--Jimmy Creek fan apex	47
	C.	Buried soil horizon--Slide Creek fan apex	47
	D.	Exposure of recent mudflow--Willow Creek	47
8:	A.	Boulder capped by flood-debris--Wolf Creek . . .	52
	B.	Summer snow banks--Bear Creek	52
	C.	Vertical accretion from overland flow--Jimmy Creek	52

PLATE			FOLLOWING PAGE
9:	A.	Multiple mudflow tracks--Tundra Creek	56
	B.	Old mudflow between Bear and Tundra Creeks . . .	56
	C.	Mass movement lobe between Bear and Tundra Creeks	56
10:		Recent mudflows in Willow Creek	56

INTRODUCTION

Between the Aklavik Range of the Richardson Mountains and the Husky Channel of the Mackenzie Delta in the Northwest Territories of Canada lies a zone of coalescing alluvial fans. Its presence was noted by early explorers and later geologists such as Camsell (1904), Gabrielse (1957), and Jeletzky (1961), but interest in it was not aroused until the winter of 1953-1954 when a search was made for a new site at which to re-locate the northern settlement of Aklavik. One potential site on the alluvial fans was investigated, but instead of finding underlying gravels as expected, the sampled fan sediments were predominantly silts. As a result of further research, a working hypothesis was suggested whereby freeze-thaw action combined with organic-acid breakdown could comminute fan material (Leggett et al., 1966). Due to the mission-oriented nature and short duration of the original field-work, there was no attempt to describe in detail the characteristics of the fan sediments or the process of fan construction.

The basic purpose of this study is to determine the nature and areal pattern of processes of fan formation in the Aklavik area, in the light of field-work undertaken during the months of June and July, 1970. In so short a time, it

was not possible to set up elaborate instrumentation to gauge the rates of erosion and deposition or the relative importance of stream action, mass movement, and eolian influences. However, it was possible to gather quantitative information regarding fan morphology and sediments and from these, attempt to deduce the processes of fan formation. It is realised that the analysis of static data is liable to misinterpretation and that it cannot replace the quantitative evaluation of active processes. However, some authors have successfully used sediment analysis, in particular, grain-size characteristics, to determine the type of environment in which a sediment was deposited, for example, Harris (1958), Mason and Folk (1958), Friedman (1961; 1967) and Sevon (1966). Discriminate functions have also been used in some cases to separate processes of deposition (Sahu, 1964; Landim and Frakes, 1968; Greenwood, 1969) and factor analysis has also been utilised (Klovan, 1966). CM patterns were introduced by Passega (1957; 1964) and modified by Bull (1962b) where mean grain-size plotted against the coarsest one percentile separates the depositional environments of some sediments. Thus precedents have been set in the use of grain-size data to assist in determining processes of clastic deposition.

Having realised the limitations inherent in this laboratory approach, field-work was designed to investigate three aspects of fan geomorphology. Firstly, radial profiles from fan toe to apex were surveyed to determine the

slope of the fan surface. Secondly, samples of sediment were collected and analysed in the laboratory to determine individual and areal characteristics of the grain-size distribution. Using these data, various discriminate techniques were applied to ascertain the dominant process of sediment deposition, and its areal fluctuations and anomalies. Data from exposures showing superimposition of sedimentary units were also analysed and interpreted.

In order to re-evaluate the existing theories proposed by Leggett et al. (1966), laboratory experiments were carried out on samples of fan sediment from the study area to determine the effect and relative importance of freeze-thaw action and organic-acid comminution in producing clay-silt-rich sediments. From these results, and conclusions regarding the dominant processes of deposition, hypotheses are proposed to explain the presence and growth of alluvial fans in this particular sub-arctic environment.

CHAPTER I

ALLUVIAL FAN CHARACTERISTICS

An alluvial fan is an accumulation of clastic sediments, whose surface forms a segment of a low cone, deposited sub-aerially from a flow produced by fluvial action and/or mass movement.[1] Alluvial fans occupy approximately the central portion of a continuum, expressing decreasing slope and increasing water content of the depositing process, ranging from talus slopes on the one hand, to river flood plains on the other. Exact boundaries between features on the continuum are very difficult to determine and therefore a certain element of subjectivity is present with regard to fan classification. However, in terms of set theory, where all elements within a set possess similar properties, it may be suggested that alluvial fans are a set having definable characteristics which distinguish them from the sets of other landforms. The discussion which follows outlines briefly some of these "definable characteristics".

Fan morphology

Some attempts have been made to quantify fan shape

---

[1]This definition is suggested by the author, as examination of the literature concerning alluvial fans yielded no statement which satisfactorily included both fluvial and mass movement processes.

by utilizing ratios relating drainage basin area to fan area and fan slope (Bull, 1962a, 1964a; Denny, 1965; Melton, 1965) and significant correlations have been produced.

Studies of the linear characteristics of fan shape have concentrated mainly on radial profiles. Krumbein (1937) first plotted fan elevation against distance from the geometric apex and found that a strong exponential relationship existed. Blissenbach (1952) graphed fan slope in degrees against distance from apex and found a similar exponential correlation. In a detailed study, Denny (1965) plotted the radial profiles of thirteen fans and concluded that although the slopes were far from regular, they were obviously concave upward and there was no break of slope between the canyon and fanhead area at the geometric apex. Other authors have noted this fact, for example, Kesseli and Beaty (1959) and Bull (1964a) and it has been stated that:

> 'the steepness of the alluvial fans is in direct relationship to the steepness of the mountain canyons providing the debris out of which they are constructed' (Kesseli and Beaty, 1959, p. 10).

In the literature concerning fans, some emphasis has been laid on the distinction between the geometric apex and the active apex of a fan. The latter is the "locus of deposition" which may move down-fan as fanhead trenching occurs. Fanhead trenching is a feature commonly noted on alluvial fans (Eckis, 1928; Buwalda, 1951; Beaty, 1963; Bull, 1964a). Eckis suggests five possible causes of fan dissection, at

least four of which have been adopted by other authors.

Dissection in the "normal course of the cycle" is favoured by Eckis (1928) and Blissenbach (1954), while Melton (1965) suggests that fan trenching is caused by the lowering of base level by trunk stream rejuvenation at various times in the Pleistocene.

Increased discharge due to climatic change, river capture, forest fires, or overgrazing of vegetation may initiate erosion (Bluck, 1964; Bull, 1964c), but Lustig (1965) proposes the opposite in the form of climatic dessication producing density flows of high tractive force. An alternation of debris flows and water flows is suggested by Hooke (1967) who concluded that fanheads are "born incised".

Uplift, increasing the slope of the whole fan or a portion thereof is discussed in considerable detail by Bull (1964b) who attempts to explain fan segmentation in terms of accelerated erosion. A fan segment that appears as a straight line (in radial profile) may be the result of rapid uplift of the drainage basin, followed by a period of little or no uplift, during which the stream channel and fan attain a common slope. Fan profiles are therefore an indispensable aid to morphological interpretation, especially where change in base level or uplift of source area is thought to have occurred.

Process

There is evidence to suggest that alluvial fans can

be built up either by fluvial action, or by flowing forms of mass movement such as mudflows, or by a combination of both. For example, Eckis (1928) assumed that the Cucamonga fans in California were laid down by running water, whereas Winder (1965) describes an "alluvial" cone constructed by a single mudflow in the Canadian Rockies.

Blackwelder (1920) was first to draw attention to the viscous, high sediment content type of flow which carried many boulders and was, in some cases, as poorly stratified as glacial till. He suggested four factors necessary for mudflow development--unconsolidated material that becomes slippery when wet; slopes steep enough to induce flowage in viscous material; intermittent water supply of the "flash flood" variety; and insufficient protection of the ground by vegetation. Under more humid conditions, with a steady supply of water, streams will create flatter fans and gentler gradients (Blissenbach, 1954).

Many fans are composed of interlaminations of mudflows and fluvial sediment (Blissenbach, 1954; Beaty, 1963; Bluck, 1964; Lustig, 1965; Hooke, 1967), and Bull (1964a) defines three types of deposits laid down under these conditions--mudflows, water-laid material and intermediate sediments. However, in arid and semi-arid areas, mudflows may well be the dominant process of fan formation, with deposition by perennial streams being of minor importance (Blissenbach, 1954; Beaty, 1963).

Theories of fan formation

As Bull (1964b) and Denny (1965) have shown, there is no break in slope between drainage basin outlet and fanhead area, and therefore the theory of decreased gradient at the fanhead causing initial deposition of fan material is not tenable. More convincingly, Bull (1964a) suggests that fans are formed because the flow spreads out below the active apex, being no longer confined by a channel. Bull uses the continuity equation

$$Q = w.d.v$$

where Q is the discharge, w is the width, d is the depth and v is the velocity. Assuming that discharge remains constant, an increase in width must be accompanied by a decrease in depth or velocity or both, which will result in a decrease in competence and capacity. As infiltration of water is likely, especially where fans are underlain by gravels, the discharge will also decrease, making deposition even more probable.

Alluvial fans appear to form only where there is a fairly steep mountain front with a marked break of slope between the "foot-line" of the mountains (Murata, 1966) and the surrounding lowland. The dominant scarp may be produced by faulting (Longwell, 1930); uplift through folding (Bull, 1964a); or by glacial scouring (Sölch, 1949; Hoppe and Ekman, 1964; Leggett et al., 1966). It has even been suggested that alluvial fans are "characteristic" of structurally disturbed regions (Blackwelder, 1931). However, actual theories of fan

formation and development fall into three categories, which have been outlined by Lustig (1965) and are described below.

The Evolutionary or Davisian Theory starts with an uplifted mountain range. As the mountains slowly wear down, the fans build out, filling the basin with sediment and eventually burying the mountain remnants beneath a continuous cover of alluvium (Lustig, 1965). An early proponent of this theory was Eckis (1928) who maintained that fanhead dissection would thus occur in the normal course of the cycle. Chorley (1962) has summarised the arguments against this concept, and states that:

> "in many areas the condition is one of massive removal of past evidence and of tendency toward adjustment with progressively contemporaneous conditions. It is an impossibly restricted view therefore, to imagine a universal approach to landform study being based only upon consideration of historical development" (p. 6).

However, the evolutionary theory is correct in two ways. Some uplift may first occur to provide the requisite differential relief for the formation of an alluvial fan at some initial time t_o. Furthermore, unless an indefinite duration of uplift is postulated, then a given basin must completely fill with sediment at some finite time t_f (Lustig, 1965).

Secondly,

> "the Equilibrium or Steady-State Theory relates morphology and process in terms of dynamic systems in which mass and energy are considered as functions of time" (Lustig, 1965, p. 182).

Lustig goes on to suggest that if alluvial fans are in dynamic equilibrium with the processes acting on them, then rates

of sedimentation and erosion on a given fan will be equal. Unless these rates are equal, a fan will either grow or diminish in size as a function of the difference between the two rates. Denny (1965) for example, suggests that the movement of detritus downfan takes place during short periods, separated by long intervals during which the material is comminuted by weathering. He concludes that many piedmonts are storage areas for coarse debris in transit from highlands to adjacent basins.

Bull (1964b) also tends to support the open system theory, but adds that climatic or tectonic changes in the drainage basins may affect the rate, mode, and locus of deposition on the fans. Lustig (1965) points out that even if dynamic equilibrium is proven for one instant of time, it is still possible that changes in both the intensities and types of processes may have occurred through time. Many landforms adjust to such changes very slowly and although they tend toward equilibrium with modern processes, they may in fact be far removed from a steady-state today.

The Climatic Theory of alluvial fan formation suggests that climatic change with time has brought about changes in process and in some cases, morphology. Lustig (1965) lists eight features which he claims are indicative of climatic change--downfan shift of loci of deposition; misfit apex trenches; the presence of paired terraces, abandoned channels, hanging fans and desert varnish; greater

estimated tractive force within active channels than on fan surfaces; and extremely low percentages of clay and organic material in both surface sediments and modern mudflows.

However, many of these features can be explained by other causes. For example, shift of loci of deposition down-fan, misfit apex trenches, high abandoned channels, hanging fans and desert varnish could all result from "normal" erosion of a fan as the mountains are lowered and the stream is incised. Furthermore, uplift of the mountain range could account for all these features, and for the presence of paired terraces.

Nevertheless, on a basis of climatic change, Lustig (1965) proposes two types of fan development. He suggests that fans build upwards during pluvial phases, when water: sediment ratios are high but flows have a low tractive force. Fanhead incision results from climatic dessication, causing a decrease in water:sediment ratios, with a greater frequency of mudflows of high tractive force. The sediment removed is deposited far below the mountain front, causing the fan to build out into the basin.

Melton (1965) also invoked a climatic theory to explain a suggested relationship between fan thickness and aspect. He maintained that north-facing fans had thickest, coarsest deposits, and that the products of intensive frost action were the major sediments of deposition. However, as frost action at high altitudes is often greatest in south-

facing basins, where a maximum number of freeze-thaw cycles may occur (Cooper, 1958), this hypothesis is debatable.

Of the three theories described it is unlikely that one single explanation can be found to account for all known observations. It is highly probable, however, that each may be responsible for fan formation in different areas, at different periods in time.

CHAPTER II

THE STUDY AREA

Location

The Aklavik Range of the Richardson Mountains is a prominant scarp forming the western boundary of the Mackenzie Delta, 130 miles north of the Arctic Circle in the Northwest Territories of Canada. Between the Aklavik scarp and the Husky Channel (a distributary of the Mackenzie River, flowing along the foot of the range) lies a belt of coalescing alluvial fans, tilted slightly downward to the east. The study area is located in this region, between Mt. Gifford and Mt. Goodenough (Latitude 68°08' to 67°57') covering an area of approximately 52 square miles (Figure 1 and Figure 6).

The flat, low-lying delta of the Mackenzie River is dissected by many tortuous channels and contains a multitude of both stagnant and moving-water lakes. It is blanketed by river sediment, mainly silts, with some fine sand and clay (Mackay, 1963). The Aklavik Range rises nearly 1,000 feet within a horizontal distance of one mile as a straight, north-east scarp above the alluvial piedmont (Plate 1:A). The crest of the range rises from Mt. Gifford (2,000 feet) in the north, to Mt. Goodenough (2,800 feet) in the south. To the west there is a steep slope down to the Donna (or

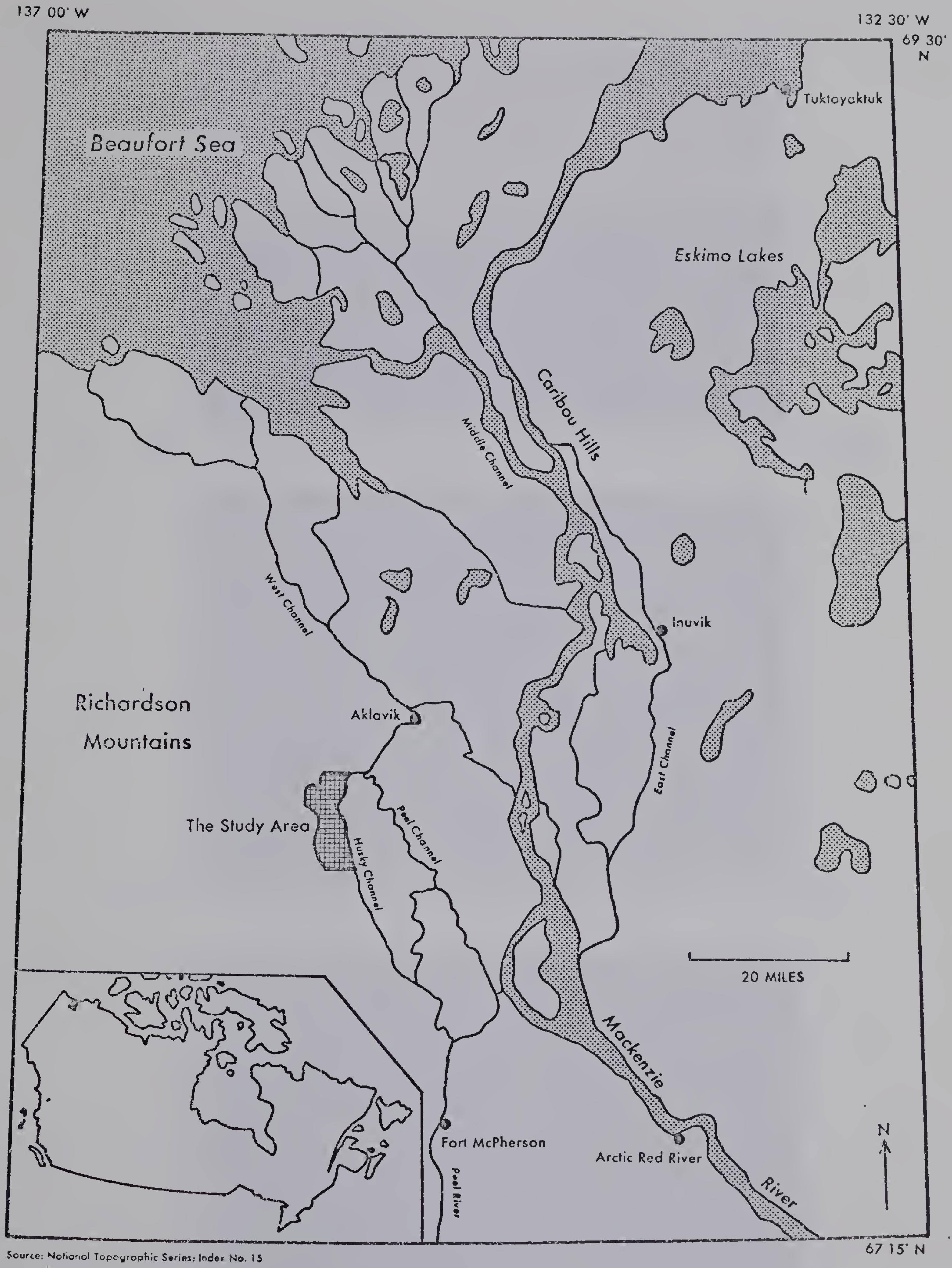


FIGURE 1: Location of the Study Area within the Mackenzie Delta

A: The Study Area looking north from Mt. Goodenough

B: "Stone garlands" on tundra above Bear Creek

Plate 1 C: Detail of "stone garlands" showing rounded pebbles

Willow) River, which flows into the Mackenzie Delta around the north end of the Aklavik Range.

Geology

The Aklavik Range is composed largely of Mesozoic, primarily Cretaceous, sediments, with some Jurassic and Palaeozoic conglomerates, sandstones, and shales (Figure 2). Throughout the range, buff coloured, fine- to coarse-grained sandstones and dark grey to black shales and siltstones predominate, although pebble conglomerates do outcrop where the Lower Shale-Siltstone Division is exposed (Figure 3, Jeletzky, 1958).

Structurally, the Aklavik Range is dominated by strike-slip faults of Tertiary age, the largest trending north, northwest and northeast. These split the area into irregularly shaped and structurally disconnected fault blocks, which differ strongly in the degree of structural complexity and age of exposed rocks (Figure 2, Jeletzky, 1961). The Cretaceous and Tertiary structures of the range are controlled by the characteristics of the basement or Precambrian rocks at depth. According to Jeletzky (1961), the break-up of the basement into fault blocks possibly took place in the late Precambrian. The surficial strike-slip faults of the area are believed to be re-activated basement faults, projected into the sedimentary cover by the later Laramide Orogeny, which not only uplifted the Richardson Mountains but also produced the Rocky Mountains to the south (Jeletzky,

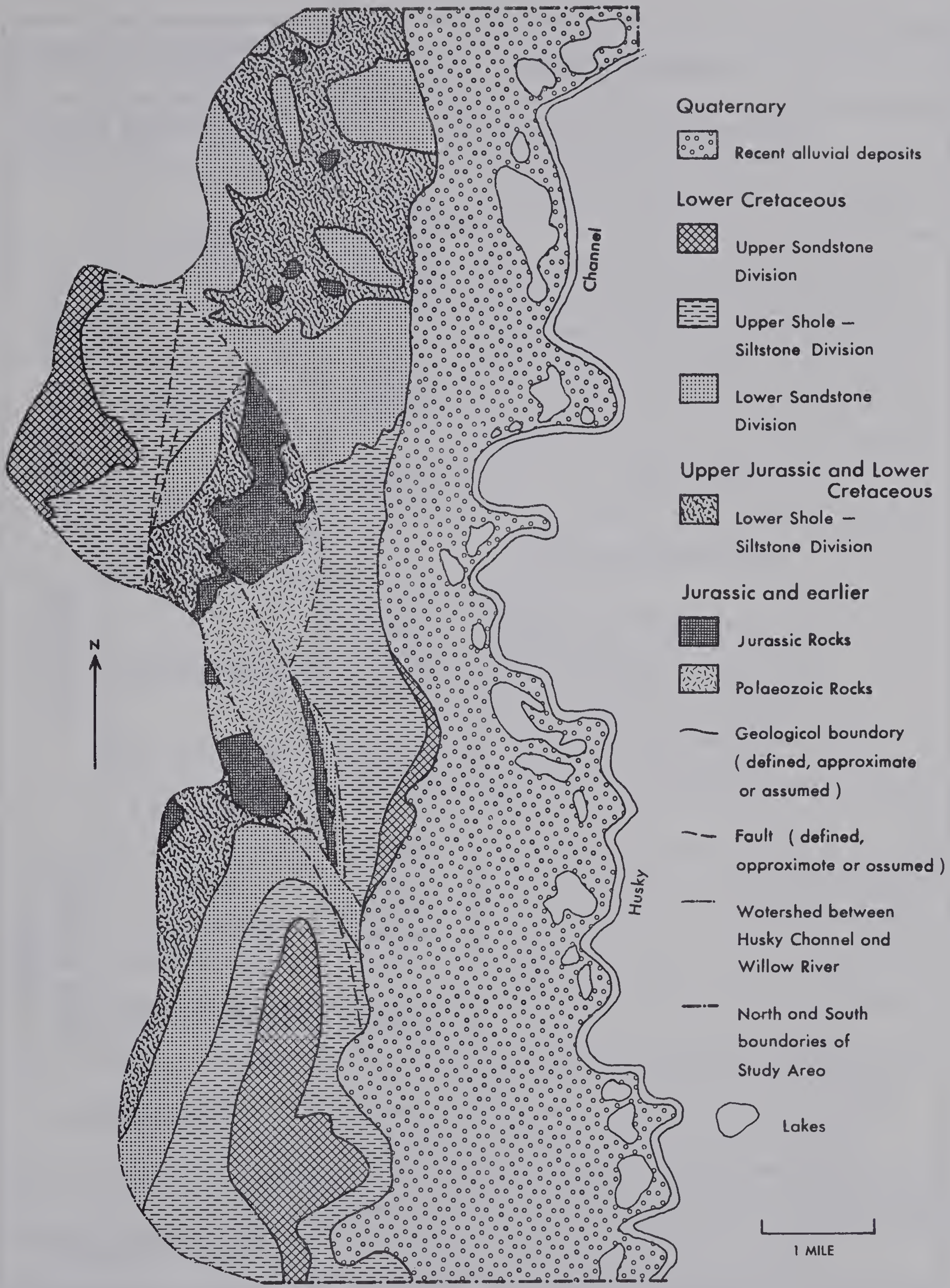


FIGURE 2: The Geology of the Study Area

Source: Jeletzky, 1958

SERIES	STANDARD STAGE	AKLAVIK RANGE	
QUATERNARY		Recent alluvial, talus, and bog deposits, stratified sand, gravel and clay	
LOWER CRETACEOUS	APTIAN	UPPER SANDSTONE DIVISION 500'-600'	Resistant, light grey, buff or rusty coloured, fine- to coarse-grained sandstone; considerable soft, grey to blackish grey, silty or clayey, shale-like sandstone and siltstone; minor gritty sandstone
	BARREMIAN	UPPER SHALE-SILTSTONE DIVISION 1500'-1750'	Dark grey to blackish grey shale and siltstone; rusty weathering clay ironstone often plentiful; considerable grey silty, shale-like sandstone near middle and top; minor resistant, light coloured sandstone near top
	HAUTERIVIAN	Overlap and Erosional Gap	
	VALANGINIAN	LOWER SANDSTONE DIVISION UP TO 650'	Resistant, light grey, white, and buff, fine- to coarse-grained sandstone; minor soft, dark to blackish grey, clayey, and shale-like sandstone; minor interbeds of coaly rocks; may be in part non-marine
	BERRIASIAN	LOWER SHALE-SILTSTONE DIVISION 1200'-1270'	Dark to brownish grey shale and siltstone; rusty weathering clay ironstone often plentiful; considerable sandy siltstone and silty sandstone in upper part; minor gritty to pebbly sandstone, pebble conglomerate, and coquina sandstone
UPPER JURASSIC	UPPER TITHONIAN		
	PORTLANDIAN		
JURASSIC		Resistant, light-grey to buff or rusty coloured, fine-grained sandstone; considerable grey, to blackish grey, silty, shale-like, fine-grained sandstone and sandy siltstone; minor grey to blackish grey shale, grit, and pebble conglomerate	
PALAEOZOIC		Red weathering conglomerate and sedimentary breccia; resistant, buff to rusty coloured, fine- to medium-grained, marine sandstone; grey, bluish black, buff, and reddish shale and argillite	

Source: Jeletzky, 1958

FIGURE 3: The Stratigraphy of the Aklavik Range

1961; Martin, 1961). Jeletzky (1961, p. 545) also suggests that some of the major faults in the area may still be active, citing as evidence epicentres of recent earthquakes.

Origin of the Aklavik scarp

The eastern slope of the Aklavik Range is such a long, straight feature that some geologists have interpreted it as a fault-line scarp (Gabrielse, 1957, p. 10). Jeletzky (1961, p. 571-572) discounted this theory by mapping all the faults in detail and suggested that the crest of the range was at one time a peneplain before a phase of post-glacial uplift rejuvenated flanking streams. Thus as the Husky Channel began downcutting, drainage became incised, with the development of high, alluvial terraces (Jeletzky, 1961), but during this study, reconnaissance showed that the only high terraces present were bedrock controlled, and were not capped by a veneer of alluvial sediment (Plate 2:A and B). Further uplift of the range, accompanied by a sharp increase in the volume of debris washed down its slopes, forced the channel away from the base of the scarp to its present position (Jeletzky, 1961).

However, there is ample evidence that the Aklavik Range was in existence during the Pleistocene. Camsell (1904) noted the presence of water-worn cobbles of gneiss on the summit of Mt. Goodenough, with a small capping of till on the east face. These observations are supported by Gabrielse (1957, p. 3-4), Mackay (1963, p. 97) and the writer's own

field observations. Mackay (1963, p. 97) also claims that the Aklavik Range is of erosional origin, but basically pre-glacial, cut by the ancestral Mackenzie River. During the Wisconsin glaciation, the Richardson Mountains formed a barrier to ice movement westwards which resulted in a straightening and smoothing off of the existing eastern scarp.

During reconnaissance, three samples of material were taken from the crest of the range, and were later subjected to mechanical analysis. The results (Figure 4) show that the grain-size curves are irregular, suggesting relatively poorly-sorted material. Lithological analysis of the particles coarser than 4 mm identified a number of granitic and metamorphic rocks, which must have been transported to the Aklavik area from the Canadian Shield, further to the south. In conjunction with the grain-size characteristics, this suggests that the material is glacial till. Furthermore, the summit of the range, as well as the eastern scarp, appears to have been glacially smoothed, while rounded and sub-angular pebbles of pink granite were found on many creek interfluves as well as on the scarp crest itself. Thus, although the Richardson Mountains as a massif may have prevented ice movement westwards, the Aklavik Range itself was at one time covered by sheet ice, possibly of pre-Wisconsin age.[1] A number of rock benches at various heights can be seen cut

---

[1]Glacial map of Canada, 1967; <u>Geological Survey of Canada, Map</u>, No. 1253A.

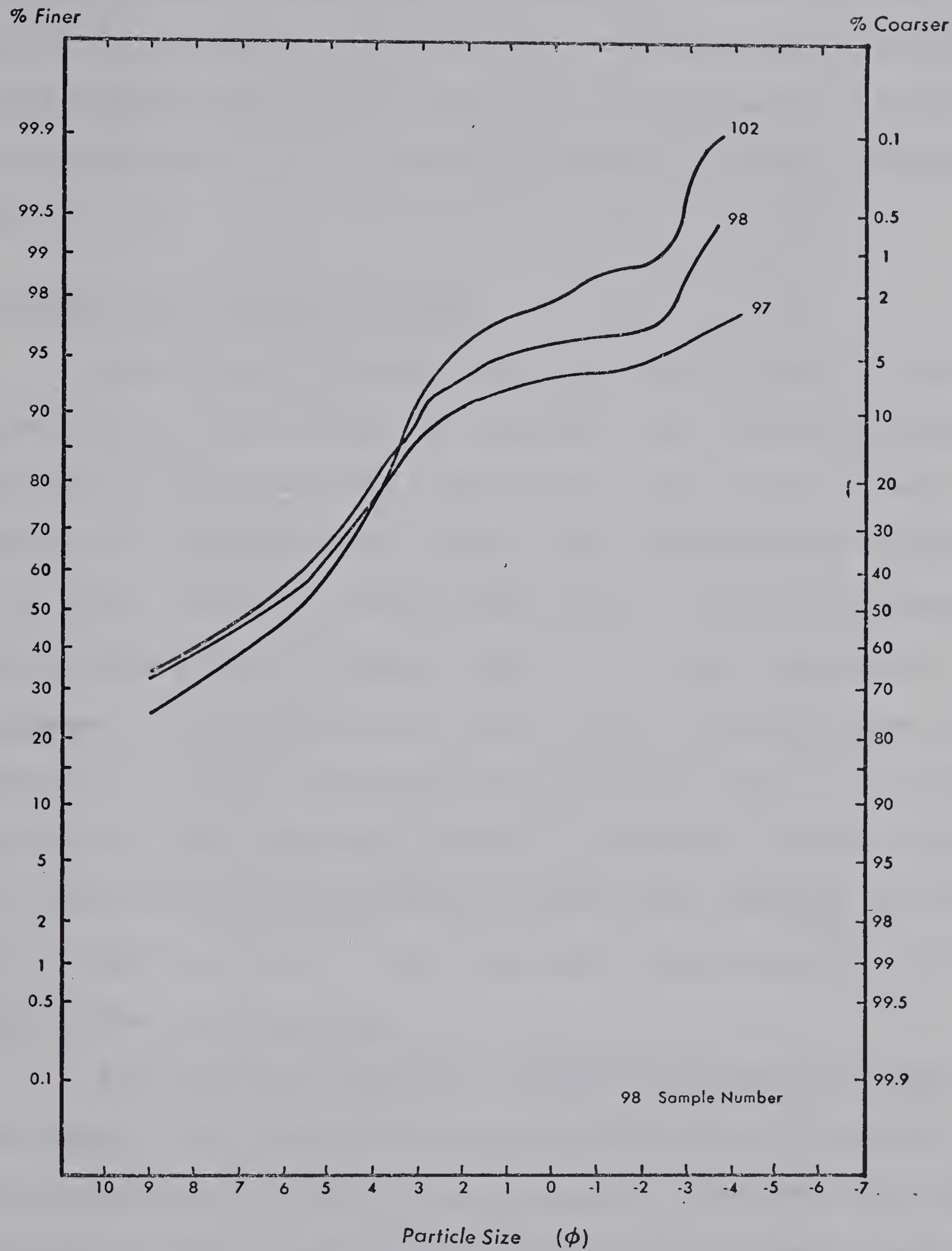


FIGURE 4: Cumulative Curves of Particle Size Distribution of Crest Samples

into the eastern scarp, with a veneer of rounded pebbles, many of them granitic (Plate 1:C). These benches and flattened interfluves may have been cut by streams of meltwater flowing marginal to the ice as it slowly stagnated (Mackay, 1963, p. 97).

Isostatic and eustatic change

According to Mackay (1963, p. 38-42) there is good evidence for three phases of isostatic and eustatic change, resulting in post-glacial submergence, emergence and submergence of the Mackenzie Delta area. Three marine terraces at 25 feet, 60 feet, and 100 feet a.s.l. suggest submergence during deglaciation (Mackay, 1957, p. 7) with subsequent emergence in the order of 50 feet around Tuktoyaktuk. More recently, a slight submergence of 10 to 20 feet is proposed by Mackay (1963), possibly caused by sediment accumulation, but since data from boreholes suggest that deposits are only 100 to 250 feet thick, it is debatable whether such a load could cause down-warping.

Post-glacial uplift of the Aklavik Range may also have taken place as indicated by the presence of two well-defined breaks of slope on most creeks. However, the lower of these may have been caused by an outcrop of more resistant rock, with which it is usually coincident, while the upper probably marks the maximum point of headward erosion since deglaciation (Plate 2:A, B, and C).

A: Valley-in-valley morphology--Fault Creek

B: Valley-in-valley morphology--Bug Creek

Plate 2 C: Terrace remnant--Bug Creek

Post-glacial geomorphology

Many denudational processes are presently at work in the study area. Fluvial action is common on gentle slopes and will be discussed in detail later. On steeper slopes, earth slumps and mudflows are significant, frequently modified by subsequent rill-wash. Solifluction is active and was especially noted on the upland tundra, where the absence of scrub made microrelief more pronounced (Plate 3:B). Since deglaciation of the area, a large landslide has occurred near Mt. Goodenough, creating a bedrock scar and hummocky area of deposition, but detailed description of this feature has been recorded elsewhere (Fraser, 1956) and is beyond the scope of this investigation.

Patterned ground is present over the whole of the study area, but three types predominate, all of which have been described in great detail by Kerfoot (1969, p. 204-280). Incipient ice-wedge polygons or "low-centred polygons" were noted on Fault Creek and Willow Creek fans, evidenced by large, polygonal, raised cracks. The most common features were earth hummocks (Sharpe, 1942; Kerfoot, 1969, p. 232) one foot high and as much as five feet in diameter. On slopes, indidividual hummocks exhibited a preferred orientation in a downslope direction, and frequently coalesced to form earth hummock stripes (Plate 3:C and 3:D). On the upland tundra, crescentic-shaped, stony terracettes were common (Plate 1:B and 1:C), which have been described as "stone

Plate 3


A: Exposed interfluve between Wolf and Willow Creeks


B: Mass-movement lobe above Jimmy Creek


C: Earth hummock stripes above Fault Creek


D: Tussocks, hummocks, and mud-boils--Tundra Creek

garlands" by Sharpe (1942, p. 277).

Fraser (1956) who also visited the area, suggested that deflation was a factor in the erosion of fines from unvegetated surfaces, and some evidence was found during reconnaissance of features visually resembling "desert pavement" (Plate 3:A). However, frost action may be an important factor in the formation of such areas, with larger particles "heaved" to the surface by ice accumulation at depth (Corte, 1966).

In general the Richardson Mountains lie within the zone of continuous permafrost (Black, 1954, p. 841: Brown, 1960, p. 162-164) and at the time of field research the permafrost surface was encountered at depths greater than six inches (Appendix B).

Vegetation

Vegetation zones conform closely to the physiographic regions of the study area. Spruce (*Picea glauca*), willow (*Salix* spp.) and alder (*Alnus crispa*) cover the delta margin, with tundra communities dominating the Richardson Mountains. The alluvial fans represent a transition zone between these two and although willow and shrub-birch (*Betula glandulosa*) are common, alder and stunted spruce occur in some areas, while the tundra communities prevail throughout.

The distribution of vegetation over the fans is directly related to present moisture conditions as they reflect the changing pattern of stream distributaries. Thus

recent washes and active channel borders are colonised by thick willow, sedge (Carex spp.), cotton grass (Eriophorum vaginatum), horsetail (Equisetum fluviatile), marsh fleabane (Senecio congestus), and marsh marigold (Caltha palustris). As the stream network changes, the onset of slightly drier conditions results in shrub-birch, bearberry (Arctostaphylos rubra), blueberry (Vaccinium vitis idaea), labrador tea (Ledum palustre), arctic lupin (Lupinus arcticus), Alaska spirea (Spirea beauverdiana), coltsfoot (Petasites sp.) and various mosses (Sphagnum spp.; Dicranum sp.; Polytrichum sp.; Nephroma arctica). The oldest, driest surfaces produce alder, Labrador tea, blueberry, bearberry, elephant's head (Pedicularis groenlandica), cloudberry (Rubus chamaemorus) and crowberry (Empetrum nigrum), underlain by dry Sphagnum spp. and various lichens (Cetraria nivalis; Alectoria ochrolenca; Stereocaulon paschale; Cladonia arbuscula). Spruce avoids the very wet areas and is frequently found as lozenge-shaped thickets, slightly higher than the surrounding marshy land. Grass tussocks are common throughout, increasing in density towards the toe of the fans. The extent to which the distributary stream network controls the vegetation pattern can be seen from the air photos, where each channel stands out as a dark line of willow or alder (Plates 4 and 5).

Soils

The characteristic features of arctic and sub-arctic

soils are associated with the presence of permafrost, not far below the surface. Tundra soils are moist as precipitation cannot penetrate to depth, but some other Arctic soils are well-drained, and during the summer, soil temperatures are considerably lower than ambient air temperatures. As the annual growth increment of vegetation is limited, the addition of organic residues to the soil is small and decomposition is slow due to the weak activity of micro-organisms (Kononova, 1966, p. 427).

Mackay (1958, p. 1) has drawn attention to the presence of a discontinuous, subsurface, organic layer, one inch to several feet thick lying close to the permafrost surface throughout the Western Arctic. This is best developed in silty to clayey soils on slopes of less than 10° as noted by Leahey (1947, p. 460) who gave a short description of the soils between the Husky Channel and the Aklavik Range. He stated that:

> "in the depressions and on the lower slopes of the ridges and knolls, organic soils covered the ground to an unknown depth, but on the upper slopes and crests of the ridges and knolls, mineral soils were found, . . . (with) a comparatively thin covering of organic matter."

Leahey described pH values ranging from 6.2 to 7.2, and permafrost was encountered at twenty inches.

Pihlainen, Brown and Johnston (1956, p. 10-11) describe the "soils" of the alluvial fans in the study area, but in fact their cores were of fan sediment, with analyses of sedimentary facies rather than soil horizons. During

field-work, however, over one hundred pits were dug by the writer, and a generalised description of the local soils made. The most common sequence was as follows:-

3" - 0"	Moss
0" - 4"	Dark black, or brown humus.
4" +	Fan sediment, usually light, grey clay-silt, grey-yellow sand, or fine, black gravels.

Veins and lenses of ice were encountered at all depths below 0 inches with many buried soil horizons represented by clayey layers, containing malodourous, decomposing, vegetable matter and stalks.

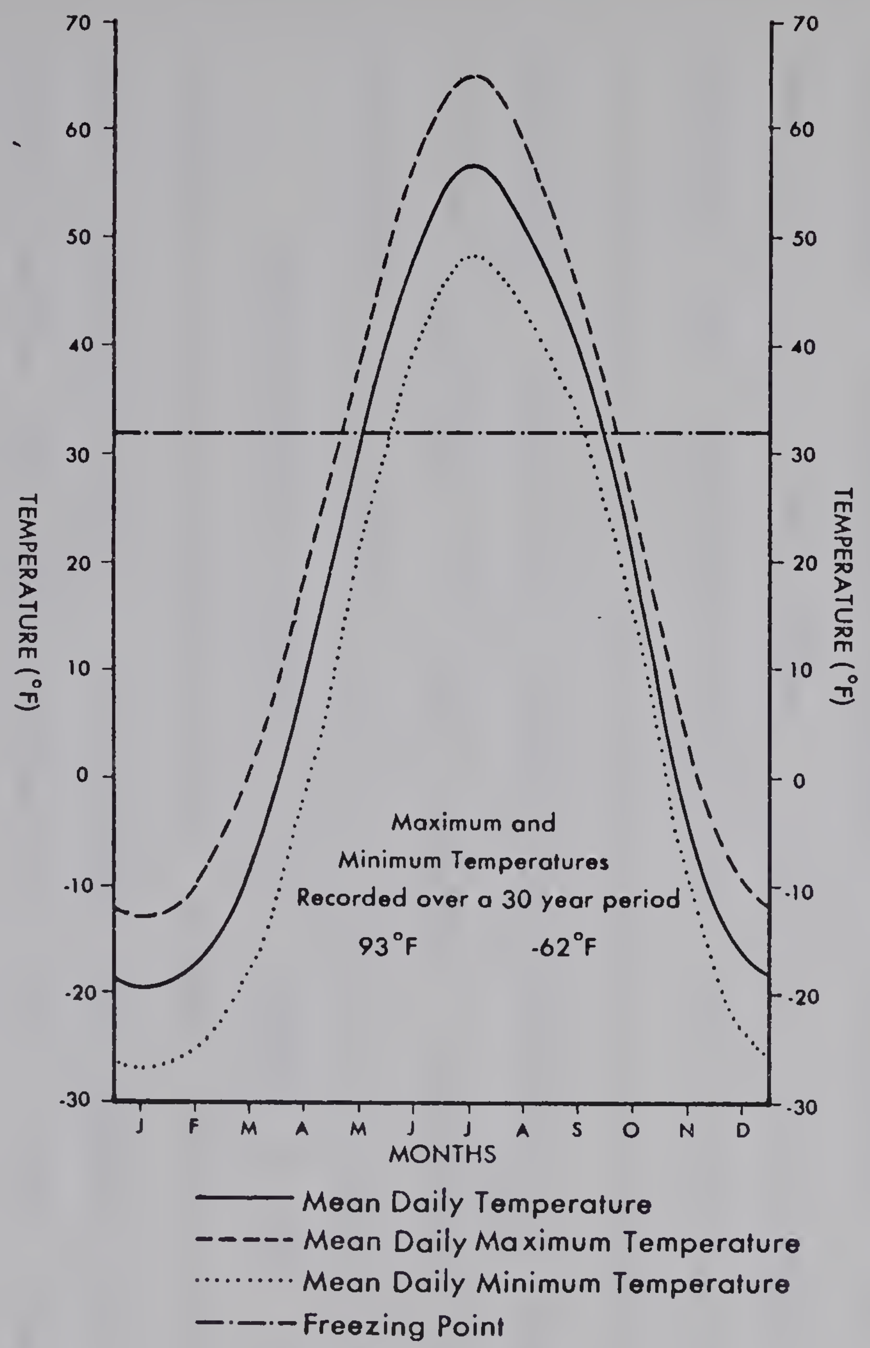
Climate

Mean climatic values are available for Aklavik for a thirty year period from 1931 to 1960. However, Aklavik is located on the delta, twenty miles north of the study area, while the fans are backed by the Richardson Mountains. Although mean temperature data are comparable, precipitation and wind conditions may differ considerably between the two sites.[2]

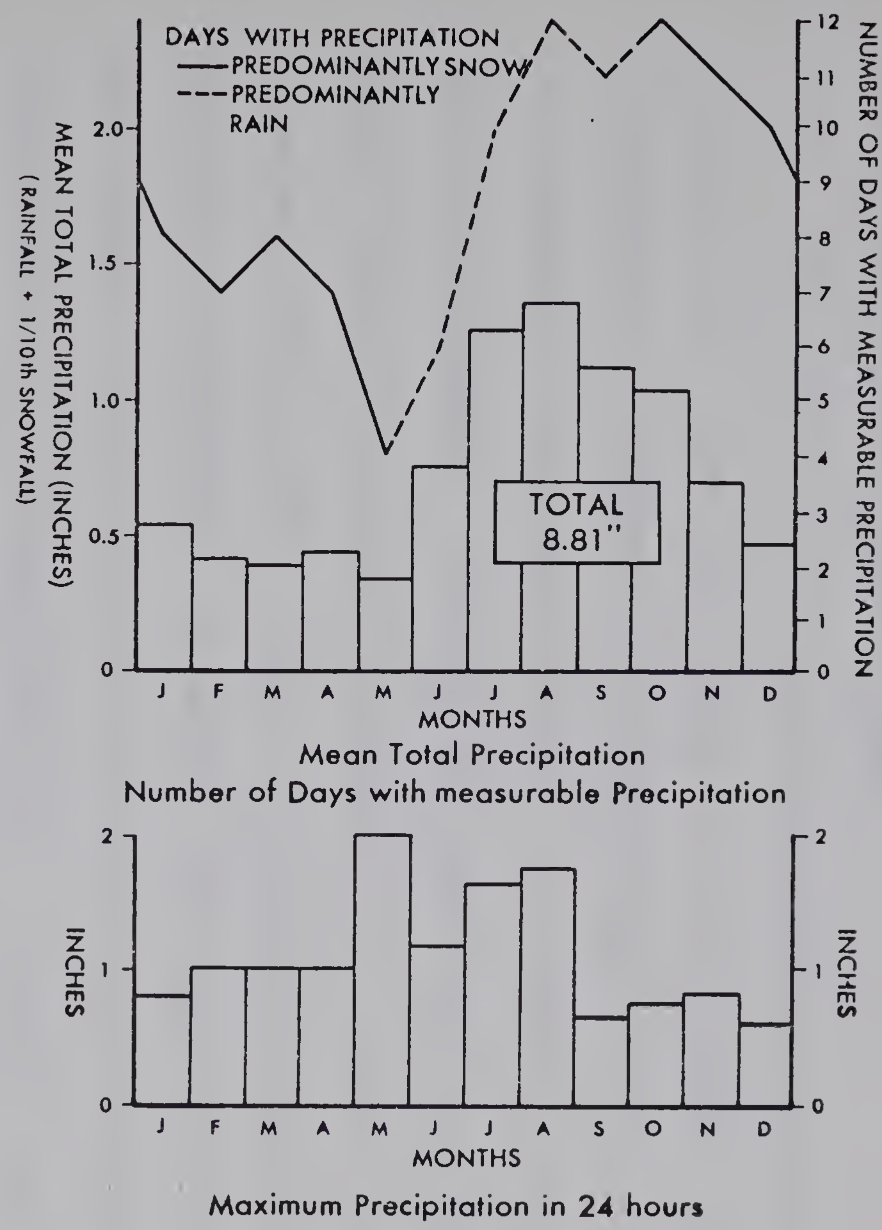
Relevant temperature and precipitation data for Aklavik are given in Figure 5. Only four months have mean temperatures above freezing point, the highest value of 56.5°F occurring in July. Five winter months have mean temperatures

---

[2]Pers. comm., J. K. Fraser, Ottawa.



TEMPERATURE



PRECIPITATION

FIGURE 5: Climatic Data for Aklavik: 1931-1960

Latitude 68°14' Longitude 135°00' Elevation 30'

Source: D.O.T., Ottawa; Met. Branch; Climatic Normals, 1968

below 0°F with the lowest value of -19.9°F in January. The average frost free period each summer is only sixty-six days, from June 15th to August 20th.

Rain has never been recorded between November and February, but snow has fallen in all months. Mean total precipitation is computed by adding rainfall to one-tenth of the snowfall, with peak values for Aklavik occurring between June and November. During the first part of this period, water evaporated during snow-melt is returned to the ground by summer convective storms, increasing local run-off. By the end of September, however, low temperatures result in a snow cover, retaining all moisture until released by warmer conditions the following spring. Although mean total precipitation for Aklavik averages 8.81 inches per year, delimiting it as a Dwc climate according to the Köppen classification, the comparable figure for the Aklavik Range may be higher due to the orographic influence of the Richardson Mountains.[3] Values for maximum precipitation in twenty-four hours are greatest from May to August, augmenting normal run-off and locally causing rapid increase in stream discharge.[4]

According to Leggett et al. (1966, p. 18), the strongest winds at Aklavik occur in June, with an average of only 8 miles per hour. In November and December the winds average less than 5 miles per hour. Most commonly

---

[3]Loc. cit.

[4]From field observations.

the wind comes from the north or northwest, blowing inland from the Beaufort Sea, but for almost one-third of the time it is from the south or southeast. Dominantly northwesterly winds were also noted by Kerfoot (1969, p. 21) on Garry Island, and by Lambert (1968, p. 11) at Canoe Lake, Richardson Mountains. However, local wind conditions in the study area are greatly modified by the proximity of the Aklavik scarp, resulting in funnelling, turbulence, and a diurnal cycle of anabatic and katabatic winds.

In general, the main features of the climate are the short, warm summers; the long, cold winters; the low precipitation with summer maximum; and the modification of climatic factors by the nearby mountains.

CHAPTER III

EXPERIMENTAL DESIGN AND RESEARCH TECHNIQUES

Selection of fans for detailed study

The delimiting of boundaries between fans, based on air photo interpretation and field observation, was somewhat arbitrary, as the belt of coalescing fans lies unbroken between Mt. Gifford and Mt. Goodenough. In many cases, the only indication of a transition between fans is a change in the type and density of vegetation. To facilitate description, all creeks and fans were named by the author, as there was a paucity of local geographical nomenclature (Figure 6).

Two contrasting fans were chosen for detailed study, these being subjectively selected on the basis of position, size, shape and amount of vegetation. Bear Creek fan, in the southern half of the study area, is approximately two and one-quarter miles long and one mile wide at its maximum, having a narrow, elongated shape (Plate 4). Fault Creek fan, to the north, nearer Mt. Gifford, resembles an equilateral triangle in shape, being one and one-half miles from apex to toe, and one and two-thirds miles across at the base (Plate 5). The most important requisite necessary for transects to be plotted accurately, was the absence of a thick vegetative cover. The thin scrub present on both fans did not seriously hinder survey work or sampling techniques.

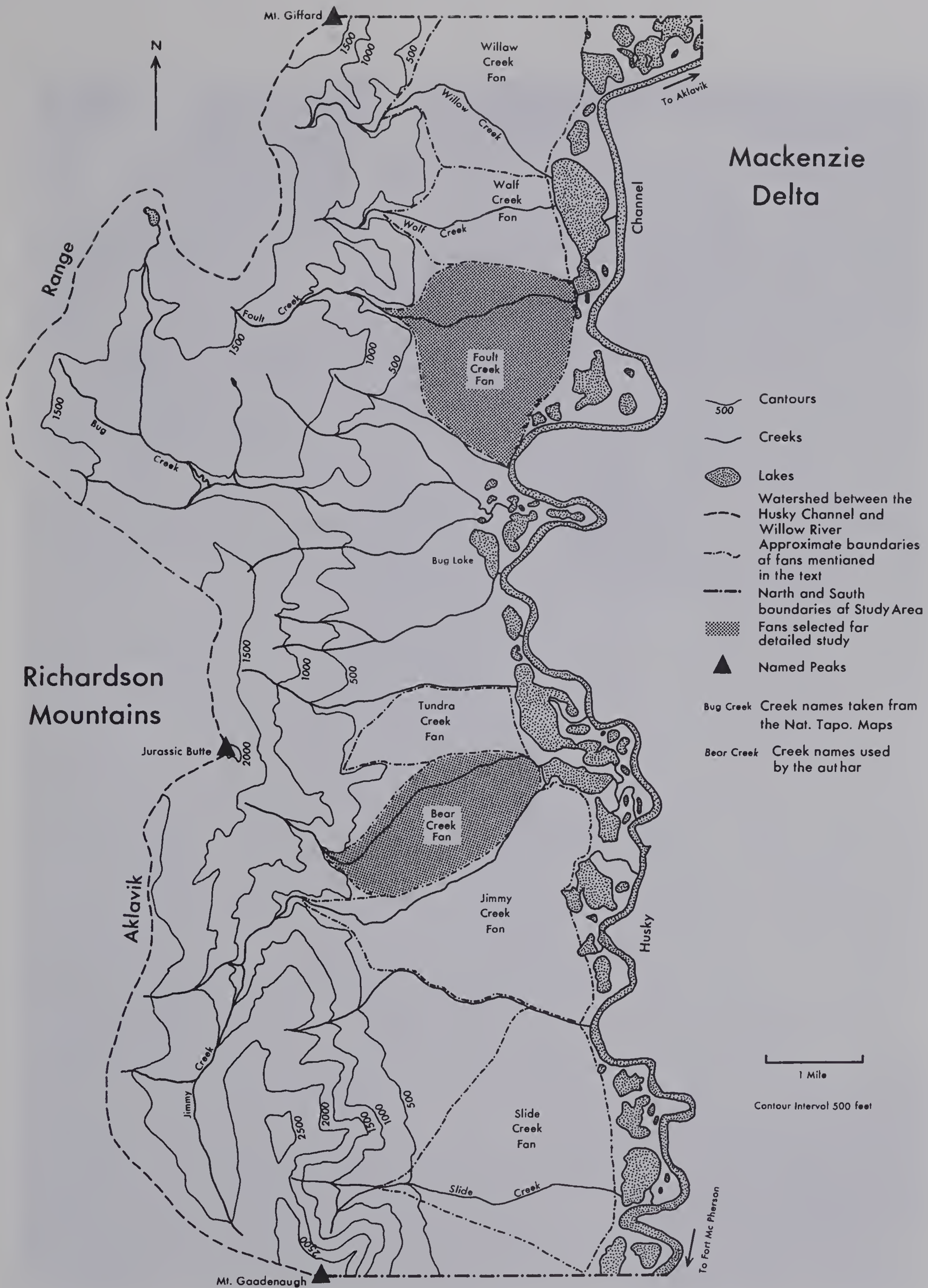


FIGURE 6: The Study Area

Source: National Topagraphic Series, 1:50000 Pravisianal, Nos. 107 B/4, 106M/14

Plate 4: Bear Creek fan
(Scale is approximate)

<u>Sampling design for fan sediments</u>

A systematic sediment sampling plan was adopted for these two fans. As the fans are not rectangular in shape, a rectangular grid spacing of sample points is not suitable. Krumbein and Pettijohn (1938, p. 15) suggest a sampling plan based on a triangular grid, the radial spacing of sample points increasing logarithmically from the fan apex. The application of this method in the field would be cumbersome, and so arithmetic spacing of sample points in a triangular network was used. As this would yield greater information about sediments near the fanhead, the sample points were "staggered" on adjacent, radial profiles.

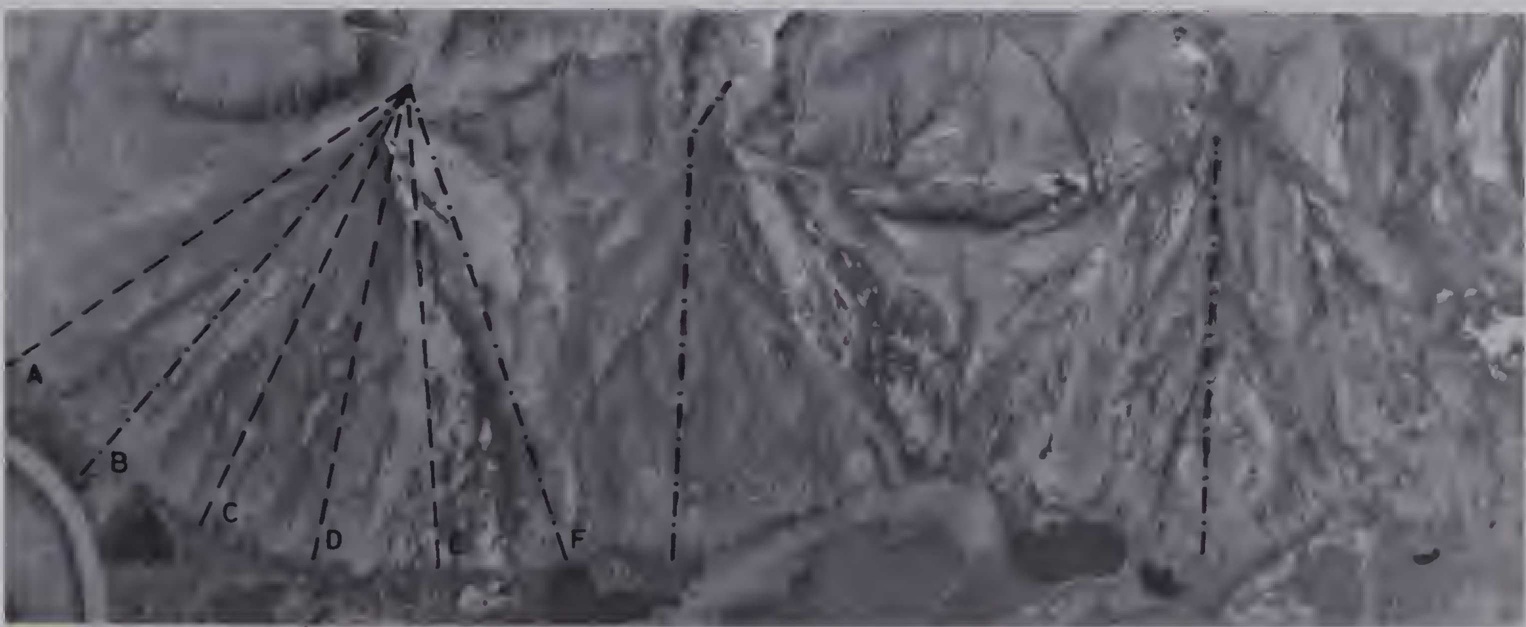
During reconnaissance, a station was set up at the fan apex, and marked with flagging tape. From this position, bearings were taken on both the northern and southern corners of the fan-toe, and the angle between them calculated. This angle was divided by the number of sample profiles needed to yield approximately fifty samples per fan, and the compass bearing computed for each radial transect. Both Bear Creek and Fault Creek fans were divided into 15° segments, giving five profiles for the former and six profiles for the latter (Plate 6:A and 6:B). Sediment sampling points were located at intervals of 1,000 feet, by pacing along these profiles, with adjacent, alternate transects starting at 0 feet and 500 feet from the fan apex (Appendix A).

As a check against these results, one profile was sampled from each of three fans where vegetation cover was

6:A

Jimmy Creek Fan Bear Creek Fan Tundra Creek Fan

6:B



Fault Creek Fan Wolf Creek Fan Willow Creek Fan

⟶ N

– – – Sampling Transect

.... Survey Line

–·–·– Profile Sampled and Surveyed

1 mile (approximately)

Plate 6: Sampling Transects and Survey Lines

sufficiently thin, namely Tundra Creek, Wolf Creek and Willow Creek fans. A sample spacing of 1,000 feet was employed for Wolf Creek and Willow Creek fans, but Tundra Creek fan, being smaller, required the use of a 750 foot spacing to give the same number of samples (Appendix A).

Field sampling techniques

At each sample point the distance from the fan apex was noted, and the slope angle measured with an Abney Level. Using a spade and axe, a pit, approximately one foot deep, was dug with its lower layers in the permafrost. A sample of fan sediment was removed by trowel from the sides or base of the pit, at a point where incorporated humus was at a minimum. Wherever possible, the sample was collected from a single sedimentation unit (Apfel, 1939, p. 67), but in cases where sediment only occurred within the permafrost, this was more difficult to achieve. Some samples were also taken from steep-angle mountain mudflows located within the drainage basins (Appendix A). A total of 170 samples were collected, placed in marked, plastic bags, and stored for shipment back to the laboratory. The depth of the sample point and the depth to the permafrost surface were also recorded (Appendix B).

Sample size

It was decided to use a sample size such that the largest particle would not be greater than 2 per cent by

weight, of the total sample. As most samples were composed of sand, silt, and clay, a minimum weight of 500 grams was chosen, and obtained in the field using a spring balance. In cases where the largest particle was obviously heavier than 10 grams, a proportionately larger sample was taken.

Surveying techniques

As the terrain to be levelled was of a rugged nature, only simple equipment was used. Backsights and foresights were taken with an Abney Level set to 0°, resting on a five foot staff. Sighting was on a twelve foot stadia rod, and the distance between staff stations was maintained at 200 feet unless an increase in slope necessitated 150 or 100 foot intervals. Heights were read from the stadia rod by a field assistant, who was directed to the exact level by the operator of the Abney Level.

Vegetative undergrowth prevented the surveying of all but a few fan profiles in the study area. The presence of a seismic cut-line across Jimmy Creek fan to the apex of Bear Creek fan allowed a line of levels to be run from a lake at the fan-toe to the fanhead zone, although the profile thus produced may be atypical due to the recession of the permafrost table under the disturbed vegetation. One other profile was surveyed up each of these fans, continuing along the stream channels past the fanheads towards the headwaters (Plate 6:A). The sampling transect on Tundra Creek fan was also surveyed.

Two lines of levels were run up Fault Creek fan to its apex, and one profile surveyed on Wolf Creek and Willow Creek fans along each sampling transect (Plate 6:B). In all cases the exact location of the profile was determined by the distribution of vegetation.

Mapping of sedimentary sequences

During reconnaissance, all good sedimentary exposures were mapped, sketched and photographed, their position being marked on the air-photographs. Where different depositional units occurred, sediment samples were taken, as described above. Most such exposures occurred as cut-banks near the fanhead, where the active channel had become incised into the fan-bay.

During the sampling of fan sediments, some pits yielded shallow exposures showing sedimentary succession. Where a number of units could be differentiated within a pit, they were also mapped and sketched, and sediment samples collected for laboratory analysis.

Mechanical analysis of samples

Each sample was subjected to the same laboratory treatment, according to a pre-determined flow chart (Figure 7). Pipette analysis of fine sediments requires that approximately 10 grams of sediment are introduced into the settling jar. Since the amount in the jar is determined by the weight retained on the 0.063 mm mesh, a rough estimate of

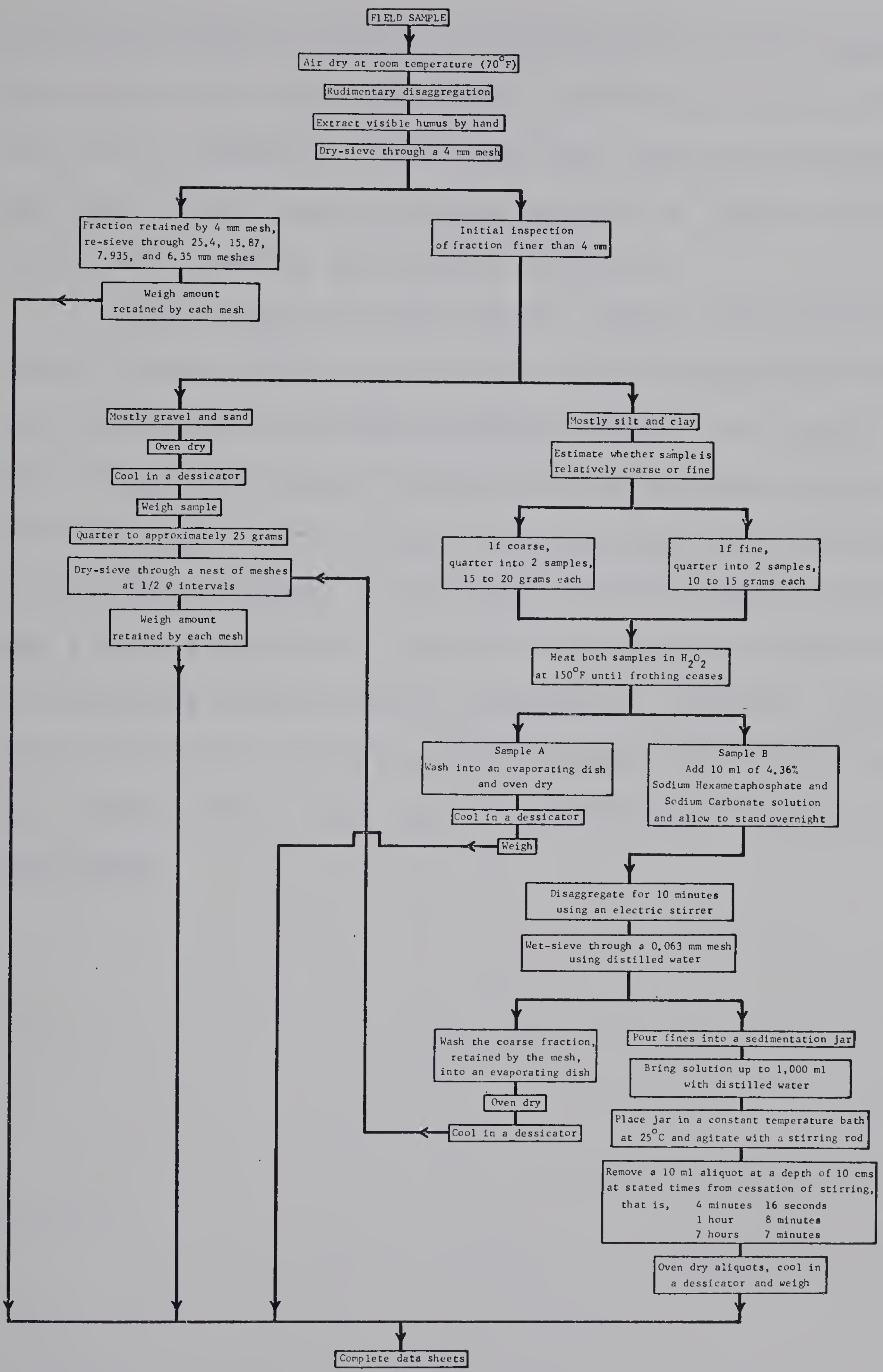


FIGURE 7: Flow Chart for Mechanical Analysis of Samples

grain-size proportions had to be made prior to the analysis. Two samples were then produced by quartering, one of which was used to determine weight loss from humus and moisture reduction. This factor was then applied to sample B which was actually used in the pipette analysis.

In the case of a few coarse samples which were dry-sieved, it was found that the pan weight was greater than 5 per cent of the quartered sample weight. As a result, the whole sample was sieved through a 0.063 mm mesh, giving the silt and clay fraction, which was then quartered and analysed by the pipette method. The weight of each fraction coarser than 4 mm was reduced by ratio to the equivalent weight of the quartered sample used for mechanical analysis. Thus the data from the three stages of analysis were converted to a common scale, ready for the application of statistical techniques.

CHAPTER IV

FAN MORPHOLOGY

The aerial view of the fans (Plates 4 and 5) emphasises the braided nature of the distributary network, as evidenced by the dark line of willow or alder which has colonised each channel. Reconnaissance showed that well defined channels were generally only present in the fanhead zone, extending some variable distance downfan. In most cases, active channels extend approximately one-third of the distance between geometric apex and toe (Bear Creek, Tundra Creek, Fault Creek, Wolf Creek, and Willow Creek) and below active apices, the flow spreads out into large areas of shallow, sluggish, muddy water. This was noticeable on all fans except that of Jimmy Creek, where a pronounced channel reaches the fan toe (Plate 4). Some small hanging fans were also noted in the drainage basin of Jimmy Creek, approximately one mile above the fan apex, but such features were not observed in other areas.

Fan shape

As the fans in the study area form a zone of sedimentary deposits, the delimitation of their borders is somewhat subjective. However, the larger valleys flanking the Aklavik

Range have a roughly triangular area of deposition between them and the Husky Channel. Many minor valleys open directly on to these fans or build their own small cones adjacent to the mountain front. In this way the fans and cones have coalesced to form a belt of sediments, with no sharp boundaries between depositional units.

Some authors have established relationships between fan area and drainage basin area (Bull, 1962a, p. 51; Denny, 1965, p. 38) but Lustig (1965, p. 133) found no significant correlation between these two variables. In the case of the Aklavik fans, the presence of the small cones encroaching on the larger fans, plus the basic subjectivity involved in assessment of fan areas would make any correlation between fan area and drainage basin area of doubtful validity.

Fan slope

Most fans exhibit a single surface or level, but Bear Creek and Tundra Creek fans possess a marked break of slope in the fanhead area. In the case of Bear Creek fan, a prominant lobe exists, backed by a higher level, which does not form an extension of the downfan surface (Figure 8). This lobe has been eroded into residual mounds ten feet high.

Eight radial profiles from six fans are shown in Figure 8. The profiles are all concave upwards, the slope at the apex being steeper than the slope at the toe. For

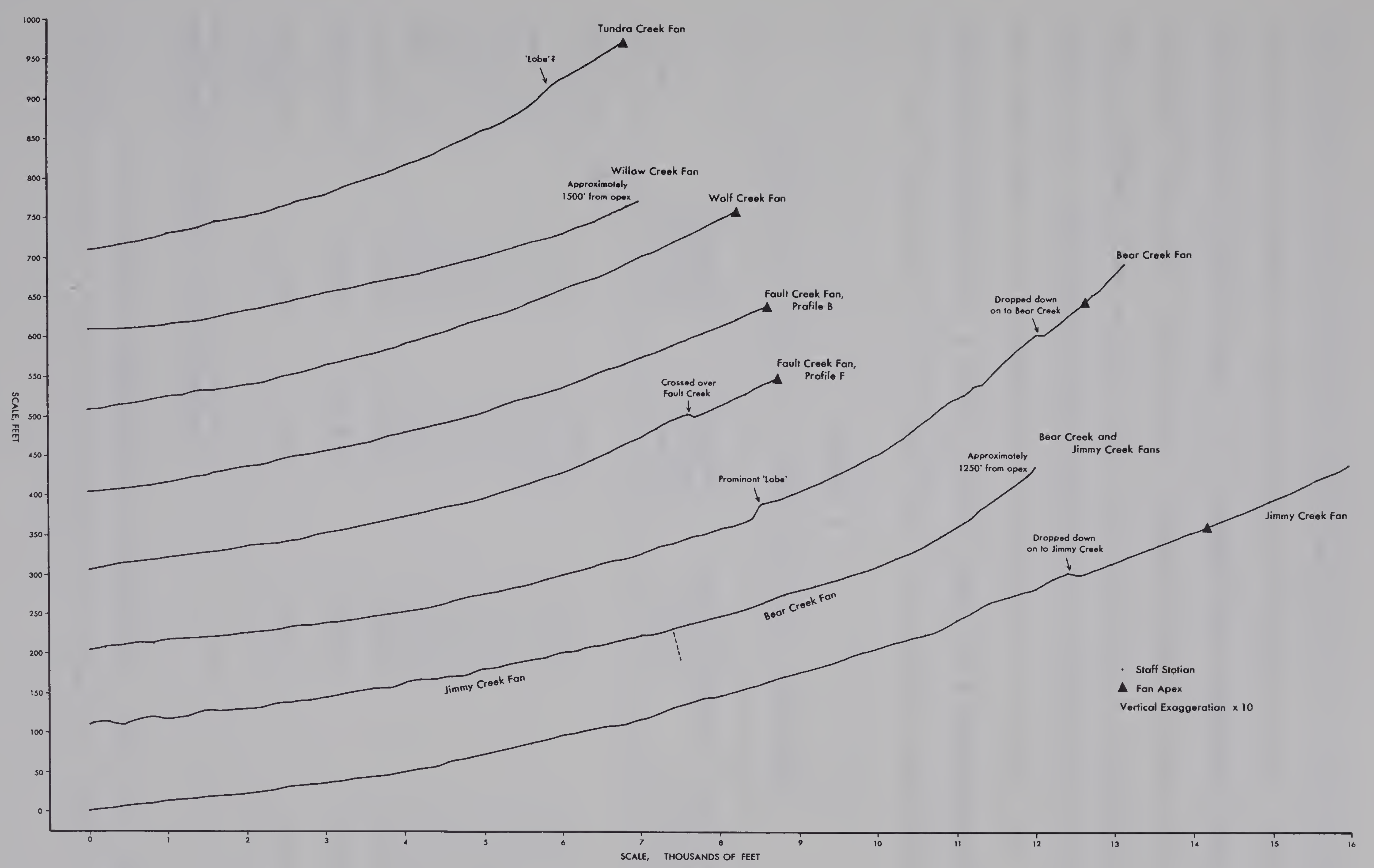


FIGURE 8: Longitudinal Fan Profiles

this reason, it was thought that there may be a logarithmic relationship between the elevation of a point on the fan and its distance from the toe. An attempt was therefore made to establish the best correlation between elevation and distance, using combinations of raw data and logarithmic transformations (Table 1). The basic, high coefficient achieved by correlating elevation and distance as measured in the field, is improved slightly by a semi-log and log-log transformation, but the improvement is so small as to be almost negligible.

TABLE 1

CORRELATION MATRIX OF MORPHOLOGICAL VARIABLES

Fan	Distance against Height	Distance against Log Height	Log Distance against Height	Log Distance against Log Height
Bear Cr. and Jimmy Cr.	0.972	0.975*	0.763	0.937
Bear Cr.	0.959	0.984*	0.787	0.969
Jimmy Cr.	0.985	0.955	0.823	0.986*
Tundra Cr.	0.981	0.969	0.876	0.996*
Wolf Cr.	0.986	0.955	0.843	0.992*
Willow Cr.	0.990	0.921	0.861	0.997*
Fault Cr. (F)	0.977	0.971	0.826	0.983*
Fault Cr. (B)	0.988	0.932	0.851	0.997*

*denotes highest correlation

It has been suggested by Blissenbach (1954, p. 178) and Beaty (1963, p. 516) that there is a break of slope

between the valley above the apex and the fan slope itself. This was disputed by Bull (1964b, p. 100) and Denny (1965, p. 8). The present study also suggests that the slopes of the drainage basin outlet and fan are continuous, as shown in Figure 8 by the profiles of Jimmy Creek and Bear Creek.

In order to compare the profiles of the Aklavik fans, the mean slopes of the eight survey lines were calculated using the formula

$$\bar{s} = \frac{h \times 1,000}{d}$$

where $\bar{s}$ is the mean slope in feet per thousand feet, h is the height of the geometric apex above the toe, and d is the distance of the apex from the toe, all in feet. The drainage basin area of each creek was also measured, and is shown in Table 2, together with the relevant mean fan slope values.

TABLE 2

MEAN SLOPES AND DRAINAGE BASIN AREAS FOR SELECTED FANS

Fan	Area (sq.miles)	Log Area	Mean Slope (feet/'000 feet)	Log Mean Slope
Jimmy Cr.	3.66	0.56348	25.448	1.40568
Willow Cr.	1.65	0.21748	27.667	1.44202
Fault Cr. (F)	1.71	0.23300	28.264	1.45116
Fault Cr. (B)	1.71	0.23300	27.577	1.44059
Wolf Cr.	1.07	0.02938	31.006	1.49150
Bear Cr.	0.76	-0.11919	35.192	1.54641
Tundra Cr.	0.51	-0.29243	39.074	1.59183

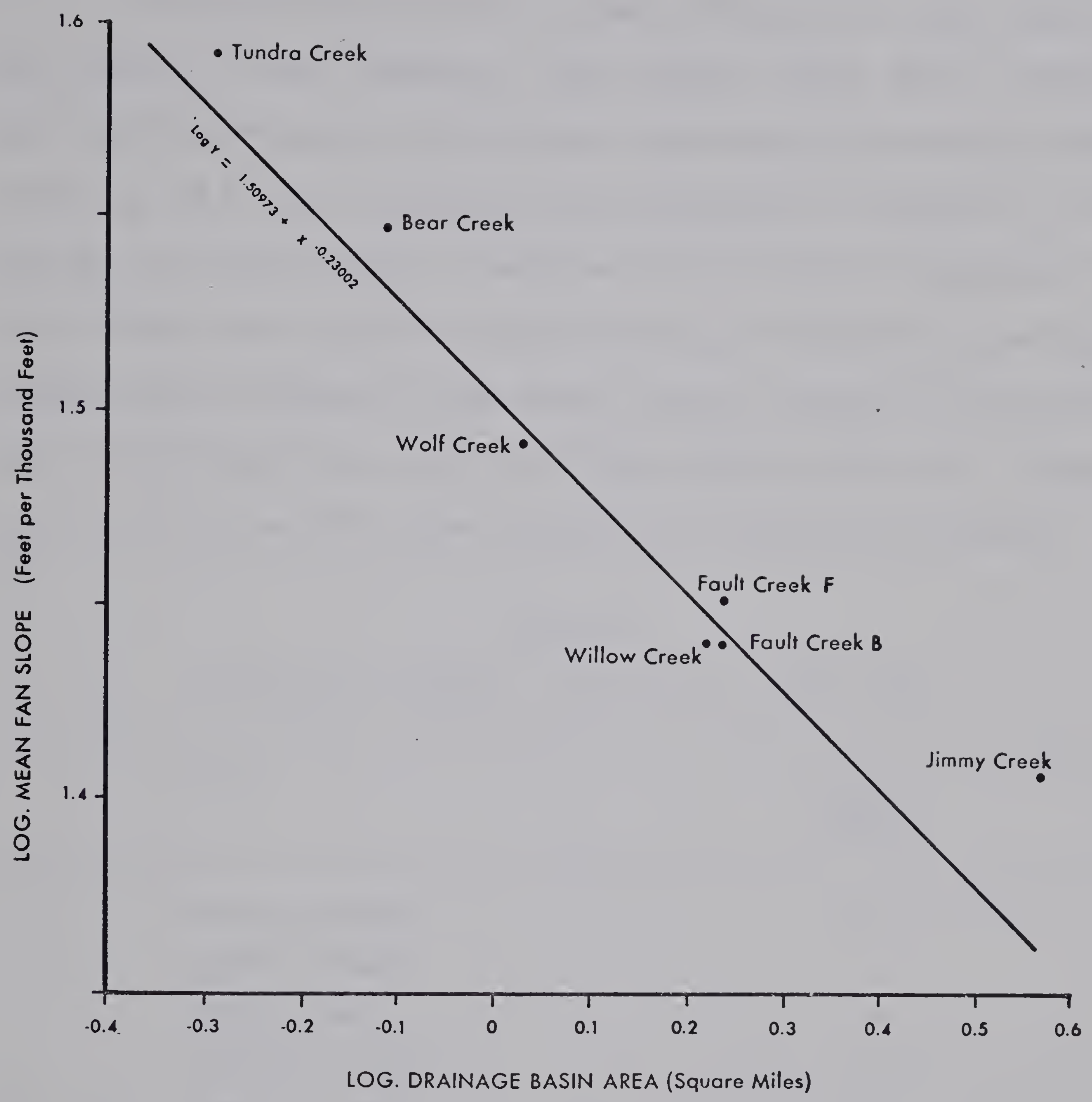
Some writers have established an inverse relationship between mean fan slope and drainage basin area, arguing that the greater discharge from a larger catchment area will produce a fan with gentler slopes (Eckis, 1928, Table 2; Bull, 1962a, p. 51; Melton, 1965, p. 23-4). Since the values in Table 2 represent the mean slopes from fan toe to apex, it is valid to correlate these with the drainage basin areas that produced them. The results of such a correlation, using a combination of arithmetic data and logarithmic transformations, are shown in Table 3. The highest coefficient of -0.968 is obtained by correlating log mean slope with log drainage basin area. With a Student's t value of -8.6 and five degrees of freedom, this is significant at the 0.001 probability level. The regression line of these two variables is given in Figure 9, showing the statistical relationship which exists between slope and drainage basin area in the study region.

TABLE 3

CORRELATION MATRIX FOR MEAN FAN SLOPE AGAINST DRAINAGE BASIN AREA

	Slope	Log Slope
Area	-0.813	-0.839
Log Area	-0.956	-0.968*

*denotes highest correlation



$r = -0.968$

Student's $t = -8.60$

Degrees of Freedom $= 5$

Significant at the 0.001 probability level

FIGURE 9 : Relationship between fan slope and drainage basin area

Fanhead incision

Fanhead incision is a common feature of many alluvial fans (Eckis, 1928; Buwalda, 1951; Beaty, 1963; Bull, 1964b) and the five theories of fanhead trenching proposed by Eckis (1928, p. 237) have already been outlined in Chapter I. Bull (1964c, p. 252) reports a maximum of 37 feet of incision into Tumey Gulch fan, Western Fresno County, California, and by comparison the Aklavik fans show little incision in the fanhead zone, other than that of Slide Creek (Table 4). Assuming that the fans are post-glacial in origin and in the

TABLE 4

DEPTHS OF FANHEAD INCISION AT THE APEX

Fan	Depth (Feet)
Slide Creek	12
Jimmy Creek	2
Bear Creek	9
Tundra Creek	2
Fault Creek	9
Wolf Creek	8
Willow Creek	5

absence of trenching on a scale similar to that reported by Bull (1964c), it can be proposed that there has been no change in base-level, nor uplift of the Aklavik Range since deglaciation. Seasonal changes in base-level occur in

response to the rise and fall of the Husky Channel during snow-melt, but these are unlikely to modify fan morphology. This hypothesis is supported by the smooth fan profiles, which would have been segmented if more permanent base-level changes or mountain uplift had taken place. As mountains wear down, and the longitudinal profile from drainage divide to fan toe becomes flatter, active channels frequently become incised into their own sediments (Eckis, 1928; Beaty, 1963, Bull, 1964b). This erosion in the normal course of the cycle, being largely absent from the study area, suggests that the fans are quite "young" in terms of a time span commencing with the earliest deposition of fan material and ending with the complete removal of the mountain source-area by denudation. This theory is also supported by the small amount of stream erosion which has taken place since deglaciation, carving small drainage basins relative to those of Willow River and Martin Creek further to the west.

As fanhead trenching is relatively insignificant in the study area, we can assume that a depositional system is dominant. During spring snow-melt, swollen streams could cause considerable erosion, but much energy may be expended in transporting the load which has been fed to the valley floors by mudflow activity, a process which will be discussed in detail later. It is noteworthy that Slide Creek fan, the only area with significant fanhead incision, has an extremely small drainage basin, cut in bedrock, resembling a cirque.

In this bedrock environment, with an absence of fine-grained lubricating material, mudflows must be infrequent, whereas in Tundra and Willow Creeks, mudflow scars were ubiquitous, with fanhead incision in the order of only two and five feet respectively.

Summary

Active channels in the study area extend downfan for a considerable distance, while below active apices, the flow spreads out into wide sheets of slow-moving water, a process which was observed during field work. Individual fans are generally triangular in shape with many adjacent cones distorting the basic configuration. Fan profiles are generally smoothly concave-upwards, with very gentle fan slopes and an absence of a break of slope at the fan apex. Bear Creek and Tundra Creek fans possess lobes in their fanhead zones, delimiting two different surfaces or levels. A strong inverse statistical relationship exists between mean fan slope and drainage basin area. The lack of significant fanhead trenching may be related to the input of sediment load by mountain slope mudflows. It is unlikely that changes in base-level, or periods of mountain uplift have occurred since deglaciation, as evidenced by the smooth fan profiles, and absence of deep fanhead trenching.

CHAPTER V

SEDIMENT ANALYSIS AND PROCESS DIFFERENTIATION

Sediment analysis can be a useful tool in enabling the geomorphologist to determine processes of deposition. The characteristics of individual particles, relevant to geomorphic studies, may be described in a number of ways, for example, size, shape, orientation, and mechanical properties (hardness, elasticity etc.). Where coarse sediment, such as stream channel gravels are under consideration, size, form, and orientation are frequently measured, but if fine sediment is concerned, analysis of shape and orientation may be precluded.

The size frequency distribution is a fundamental property of a clastic sediment, and in the case of fluvial and eolian material, provides some indication of the transport energy involved (Landim and Frakes, 1968, p. 1213). The grain-size characteristics of other sediments, such as till, colluvium and mudflow deposits, are sometimes difficult to interpret, and determination of depositional process solely from size frequency distributions is of doubtful validity (Landim and Frakes, 1968, p. 1213). Nonetheless, the cumulative curve of particle size distribution has sometimes been used as a visual description of the grain-size

characteristics of a sediment (Sharp and Nobles, 1953, p. 556; Bull, 1963, p. 248; Ruhe, 1964, p. 154; Denny, 1965, p. 5).

Visual comparisons of grain-size curves

The grain-size curves of the study area sediments were plotted, and are presented in four groups--Bear Creek fan (Figure 10), Fault Creek fan (Figure 11), Tundra Creek, Wolf Creek, and Willow Creek fans (Figure 12), together with samples from steep-angle mudflows occurring on drainage basin slopes in the mountains (Figure 13). The mudflow samples are presented for visual comparison with the alluvial fan samples. A great variety of curves is apparent, with those located to the left of centre representing coarser material than those to the right. The general 'pattern' of mudflow curves is reproduced by the finer alluvial fan material, but the coarser fan sediment stands out as a separate grouping of curves further to the left. The location of this latter group of curves was plotted, but presentation of the results will be undertaken later, in connection with the areal analysis of fan sediment.

This visual description of sediments suggests, qualitatively, that mudflow deposits are present on the fans, and that coarser fan sediments exist which may have been laid down by some other process.

Statistical expression of sediment characteristics

A number of attempts have been made to introduce an

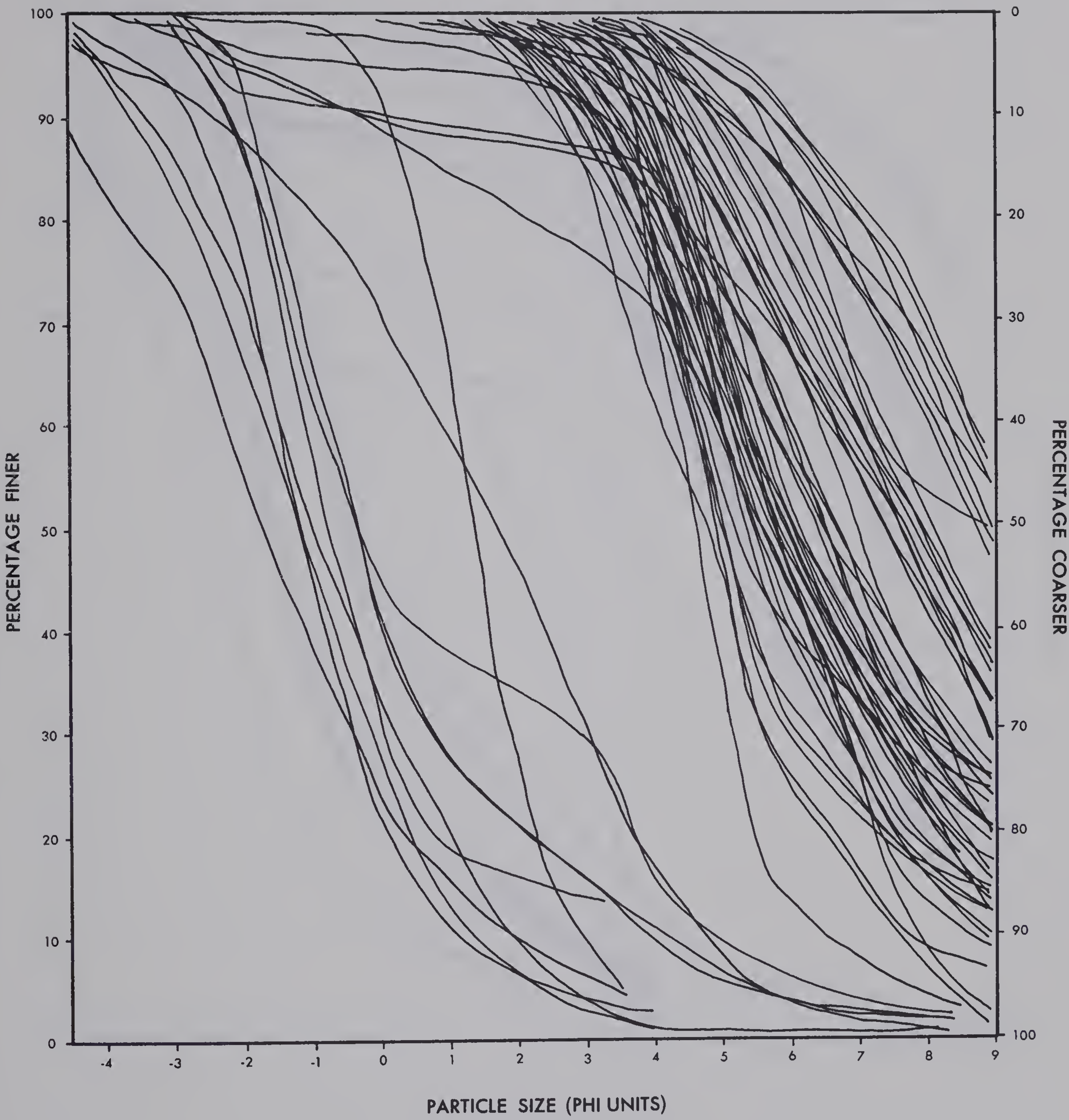


FIGURE 10: Grain-Size Curves - Bear Creek fan

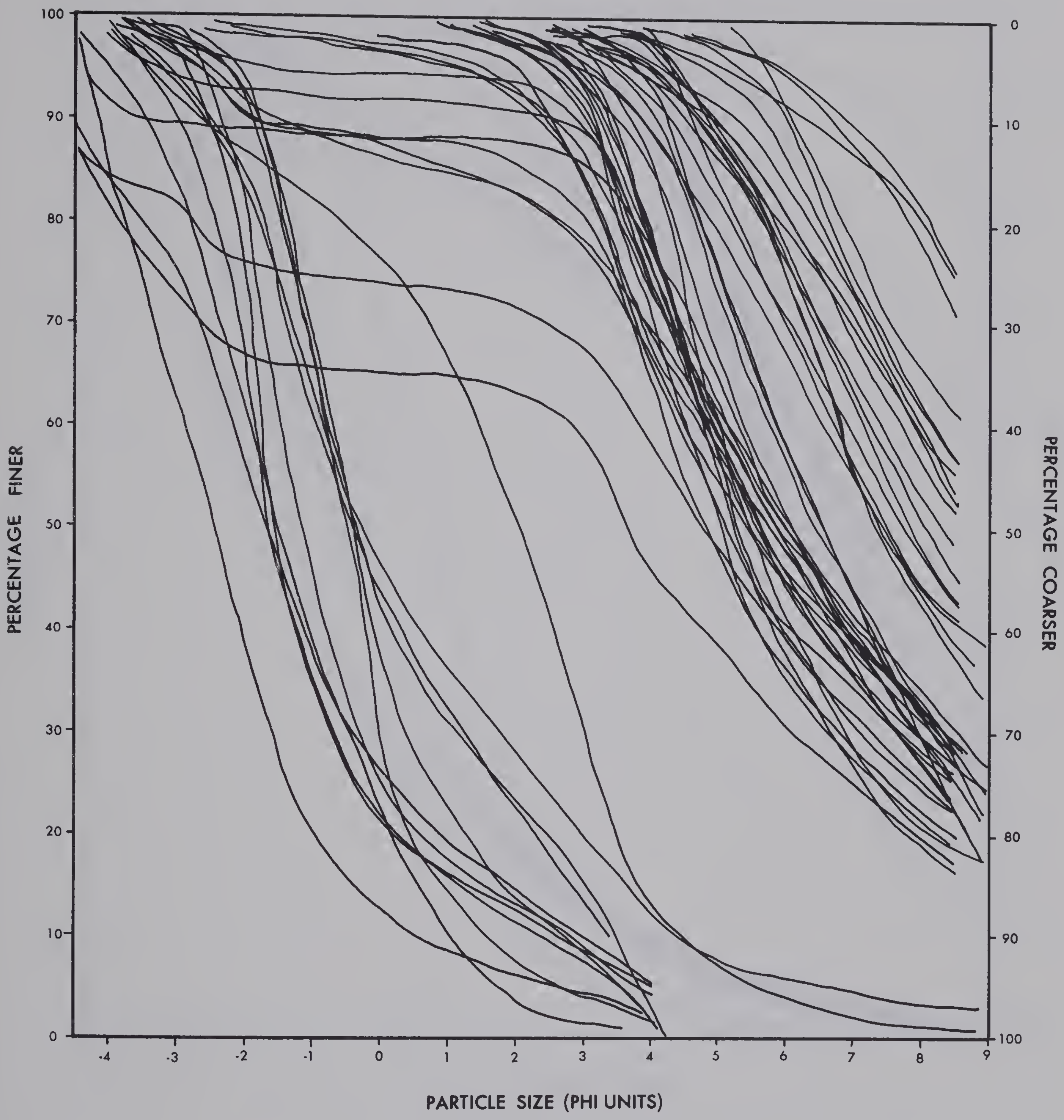


FIGURE 11: Grain-Size Curves - Fault Creek fan

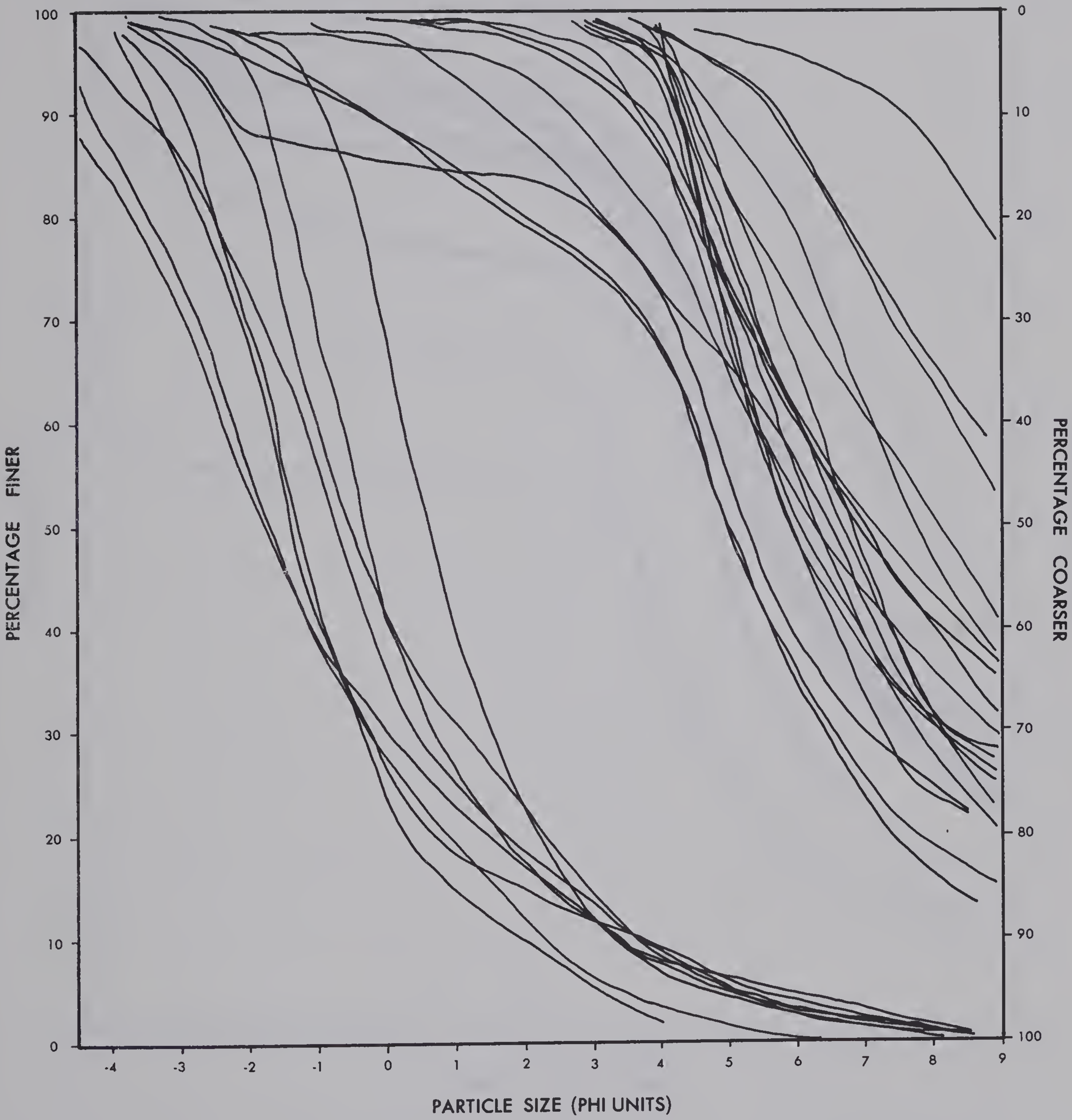


FIGURE 12: Grain-Size Curves - Tundra Wolf and Willow Creek fans

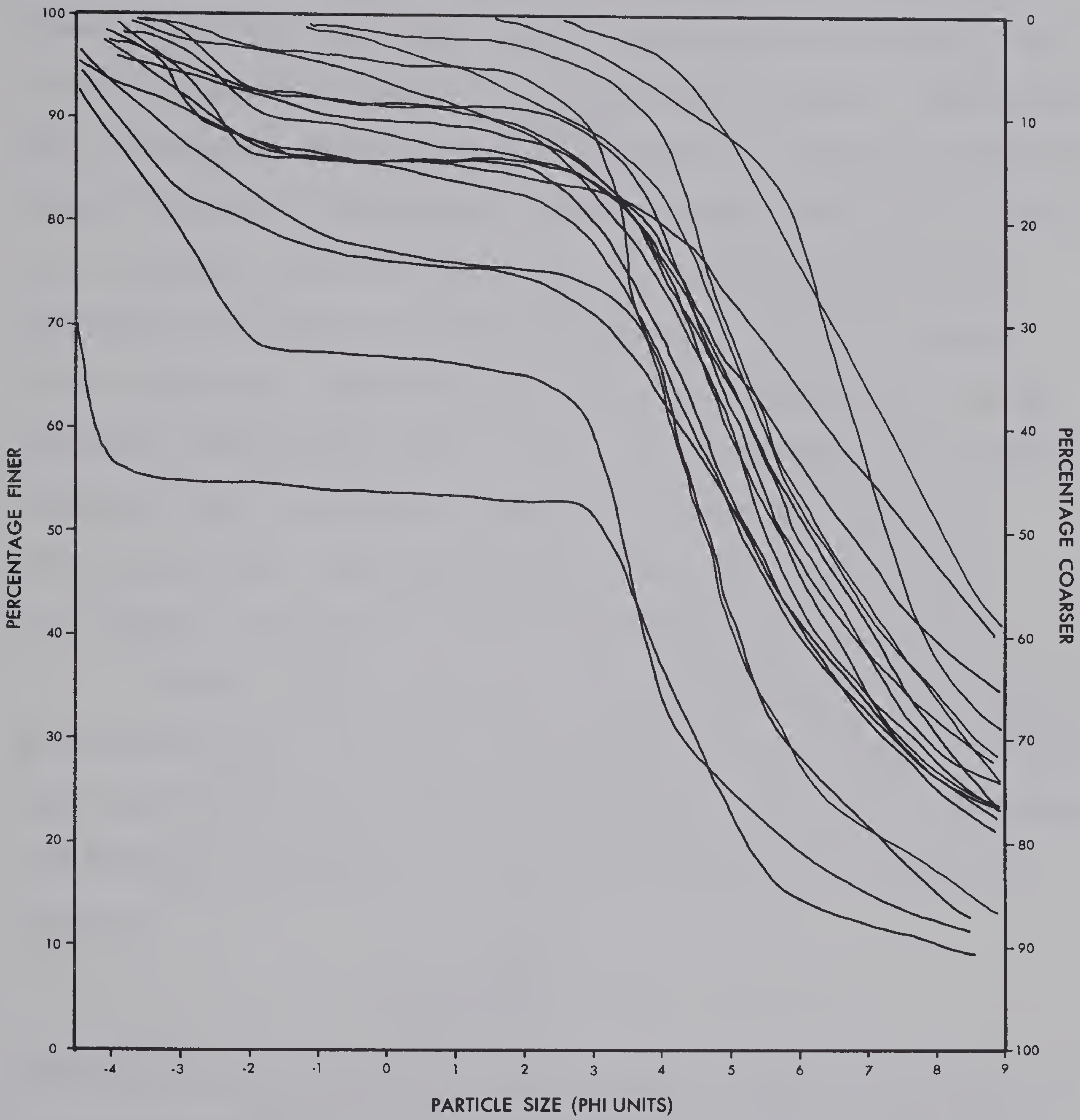


FIGURE 13: Grain-Size Curves – Mudflows

objective approach to the comparison and interpretation of grain-size frequency distributions by means of statistics. These statistics have been mainly descriptive in nature, but allow interpretive tests to be performed on them. Geologists have introduced moment measures (Wentworth, 1929) to indicate central tendency, dispersion, skewness and kurtosis of grain-size frequency distributions, but the large range between smallest and largest particle present in a sample necessitates cumbersome calculations involving a logarithmic class interval (Griffiths, 1967, p. 81). To overcome this problem, Krumbein (1936) evolved a logarithmic transformation of grain-size data, from millimetres into phi units, where $\emptyset = -\log_2 D$, D being the particle diameter in millimetres.

Trask (1932), using the cumulative percent frequency grain-size curve, took the 50th percentile or median particle size, as a measure of central tendency. Similarly, a sorting coefficient or measure of dispersion was evolved using the formula

$$S_o = \sqrt{\frac{Q_3}{Q_1}}$$

where Q_3 is the 75th percentile or upper quartile, and Q_1 is the 25th percentile, or lower quartile. As the statistics are easily derived, yet are more objective than a purely visual comparison of grain-size curves, the Trask median and sorting coefficient were computed for each field sample (Appendix C). In the case of 78 samples, the grain-size

curves did not reach the 25th percentile, and the curves were extrapolated so that a reading could be taken. The resulting values are therefore far from accurate, but it should be stressed that due to the fine-grained nature of the sediment and the open-endedness of the grain-size curves, this was the only statistical measure of sorting that could be calculated. Median values ranged from 5.545 mm to 0.001 mm for fan samples and from 2.642 mm to 0.003 mm for the mountain-slope mudflows. Sorting coefficients ranged from 36.886 to 1.605 for the fan samples and from 28.344 to 2.713 for mudflows. Although these figures are better expressions of grain-size characteristics than purely visual interpretations, neither statistic takes into account the 'tails' of the distribution, which are usually highly significant in terms of sediment analysis (Sahu, 1964). However, the similarity of ranges outlined above does support the hypothesis that mudflow deposits are present on the fans.

Since Trask's use of quartile values ignored the tails of the grain-size distribution, Inman (1952) suggested the use of a greater range of percentile values, employing Krumbein's phi transformation, for the calculation of mean, standard deviation, skewness and kurtosis statistics for normally distributed sediments. Folk and Ward (1957) modified these formulas to apply to grain-size curves which were assymetrical or bi-modal in nature (as in the case of the Aklavik fan sediments), as well as those normally distributed.

Examples of interpretive tests that can be performed on these descriptive statistics in the field of linear discriminate analysis have been outlined by Sahu (1964) and Landim and Frakes (1968). Use of such discriminate indices depends on the accurate measurement and calculation of the four Folk and Ward statistics. In many cases, however, it is not possible to calculate these values, as the grain-size curve is too open-ended. This is particularly true when samples possess a large clay fraction. Thus, out of the 170 samples from the Aklavik study area which were subjected to laboratory analysis, only 29 could be described by Folk and Ward methods. The scattered, spatial distribution of these few samples precluded their use in any subsequent analysis. The high clay fraction of the other 141 samples produced grain-size frequency curves which were too open-ended to allow Folk and Ward statistics to be calculated. Therefore some other technique was sought whereby an objective separation of process could be achieved, based on grain-size characteristics.

CM Patterns

Passega (1957; 1964) has suggested a rather specialised technique for graphically relating the median grain-size and a sorting index, and using the resultant grouping of plots to differentiate sediment types. Providing that a full range of sizes is available for transport, a condition

that is fulfilled in the Aklavik Study area (Figure 3), the maximum grain-size of a sample measures the competency of the depositing agent, and this can be represented by the coarsest one percentile (C) in microns. As already mentioned, the median (M) or 50th percentile represents central tendency, and Passega suggested that when C is plotted against M on log/log paper, patterns characteristic of the agent of deposition will be produced.

Passega's initial application was to the Mississippi River (1957, p. 1954), samples from which formed a crescentic pattern of "tractive-current" deposits containing three segments--PQ, the main section of the channel; QR, a sub-merged bar; and RS, a deep, protected part of the channel. Passega (1957) then applied this technique to ocean floor sediments, producing a similar crescentic pattern which, Passega argued, also represented "tractive-current" deposits. The plot of ocean floor sediments also produced a long rectilinear pattern, nearly parallel to the line C = M, but a considerable distance from the limiting axis, which Passega interpreted as indicating turbidity flow deposits.

Bull (1962b) adapted this technique to apply to alluvial fan deposits from Western Fresno County, California, and when plotted, all samples were scattered to the left of the line C = M. A sample plotting on the line C = M would be perfectly sorted in its coarser half, but a sample plotting to the left of this line would be characterised by

poorer sorting in this size range (Bull, 1962b, p. 213). Bull concluded that samples plotting near the line C = M, being better sorted, represented fluvial deposits, while those further from the limiting axis, being more poorly sorted, might represent mudflows. The fans in Western Fresno County are composed of readily distinguishable fluvial and mudflow sediments, and Bull plotted these to check his basic hypothesis. Passega's "long rectilinear pattern" enclosed most of the mudflow samples, while main channel deposits and samples from shallow, braided streams or from sandbars adjacent to the main part of a larger stream channel appeared in tractive-current segments PQ and QR respectively. Bull found that the RS segment was not present and therefore suggested that this type of deposition is not characteristic of alluvial fan deposits.

To test Bull's theory and to reach a higher level of objective interpretation of the study area sediments, C and M values were measured in microns for each sample and plotted on a log/log graph (Figure 14). The mountain mudflow samples from drainage basin slopes were included as a check on the fan samples, and form a reasonable approximation of the "long rectilinear pattern" suggested by Bull as representing mudflow deposits. Also present is the PQ segment of main channel deposits. The plots which lie within this segment are also those samples visually distinguished as having grain-size curves which were significantly different from those of

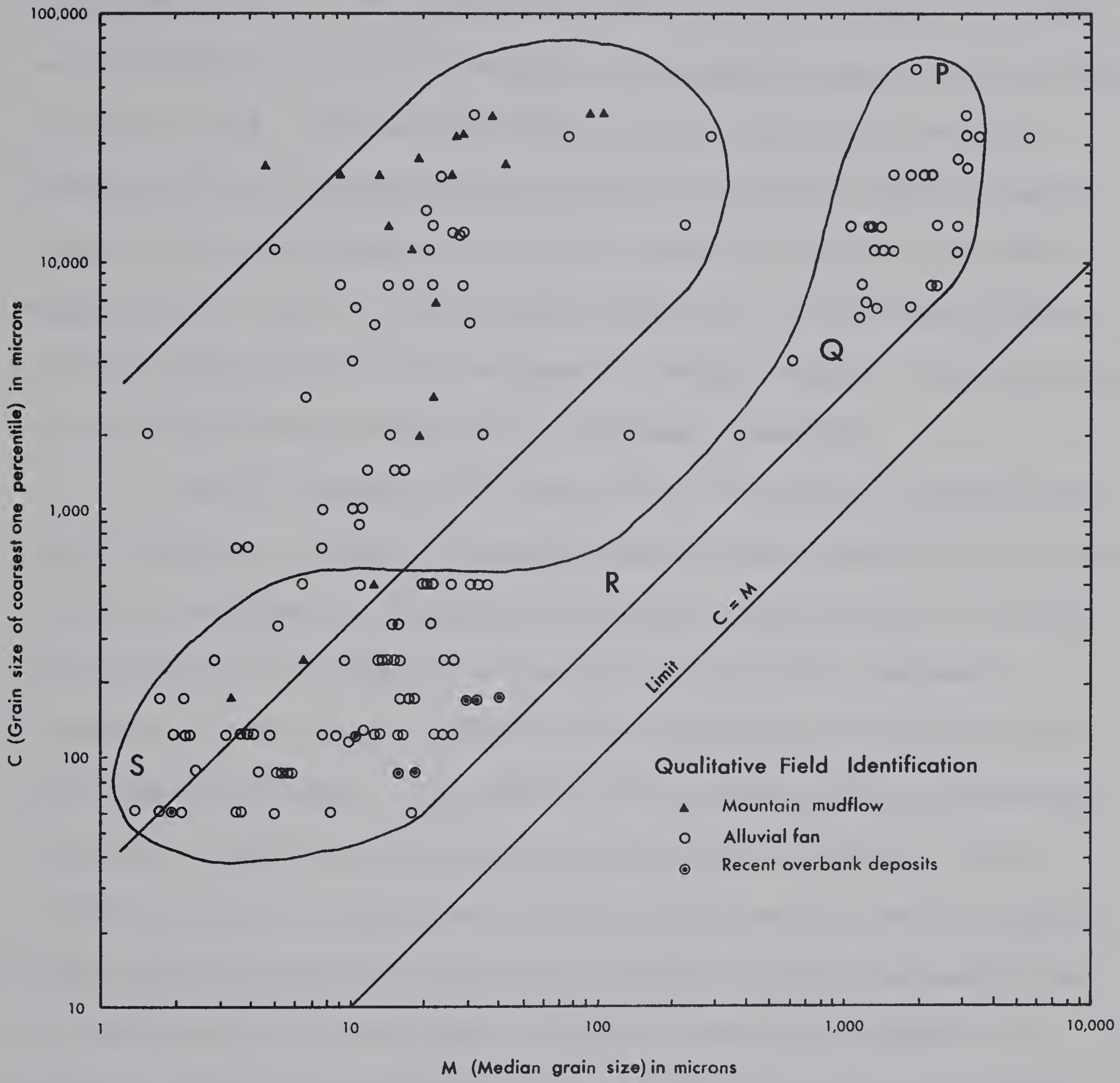


FIGURE 14: CM Patterns of Surficial Deposits from the Study Area

the mudflows (Figures 10, 11 and 12). The absence of the QR segment poses a problem of interpretation and definition. Assuming that the PQ segment of main channel deposits represents lateral accretion and the QR segment represents braided streams, since fluvial activity on alluvial fans is frequently of the braided stream type, one would expect the QR segment to predominate, as Bull's results indicate (1962b, Figure 2, p. 214). Its absence from the CM patterns representing the Aklavik fan sediments cannot readily be explained, and could provide a basis for further research.

The RS segment of Figure 14 is extremely conspicuous and contains a number of samples taken from spreads of recent overbank sediment. Passega's original description of this environment as a "deep, protected part of the channel", suggests a low energy system with deposition of fines from the suspended load. In terms of an alluvial fan, this could represent vertical accretion of overbank deposits. Bull (1962b, p. 214) concludes that the absence of the RS segment from the CM patterns of Western Fresno County fan sediments may be due to the carrying of finer material on down the slope. Vertical accretion on the Aklavik fans may be more common due to the local hydrologic regime (to be discussed later), the very low angle of fan slope, especially near the toe, causing lower velocity of flow, and the greater entrapment by a stable vegetation mat which exists over most of the fan surface.

A most significant feature of the Aklavik CM patterns is the presence of a large number of fan samples within the zone previously described as representing mudflows, and containing plots of mudflows from the drainage-basin slopes. If this technique is valid, it would appear that the fans are composed of three types of sediment--lateral accretion deposits; mudflow deposits; and overbank deposits. To test this hypothesis, the location of each group of samples was plotted for Bear Creek and Fault Creek fans (Figure 15, 16 and 17).

The mudflow deposits (Figure 15) occur generally near the fan apices, although a number of locations downfan cannot be explained. The lateral accretion deposits (Figure 16) do not indicate linearity except possibly on Fault Creek fan at its apex, where plots of channel sediment conform fairly well to the actual active channel of Fault Creek, as evident from field observations and air photo interpretation (Plate 5). This channel appears to cut through the cluster of mudflow samples at the apex, and may represent re-working of mass-movement sediment by fluvial action. However, the lack of strong zonation shown by these samples is not really consistent with the concept of lateral accretion deposits from active or relict channels which one would expect to find reproducing channel patterns.

The locations of the RS plots (vertical accretion sediment) are randomly scattered over both fans, with no pattern emerging (Figure 17). Overbank flow spreads out from channels,

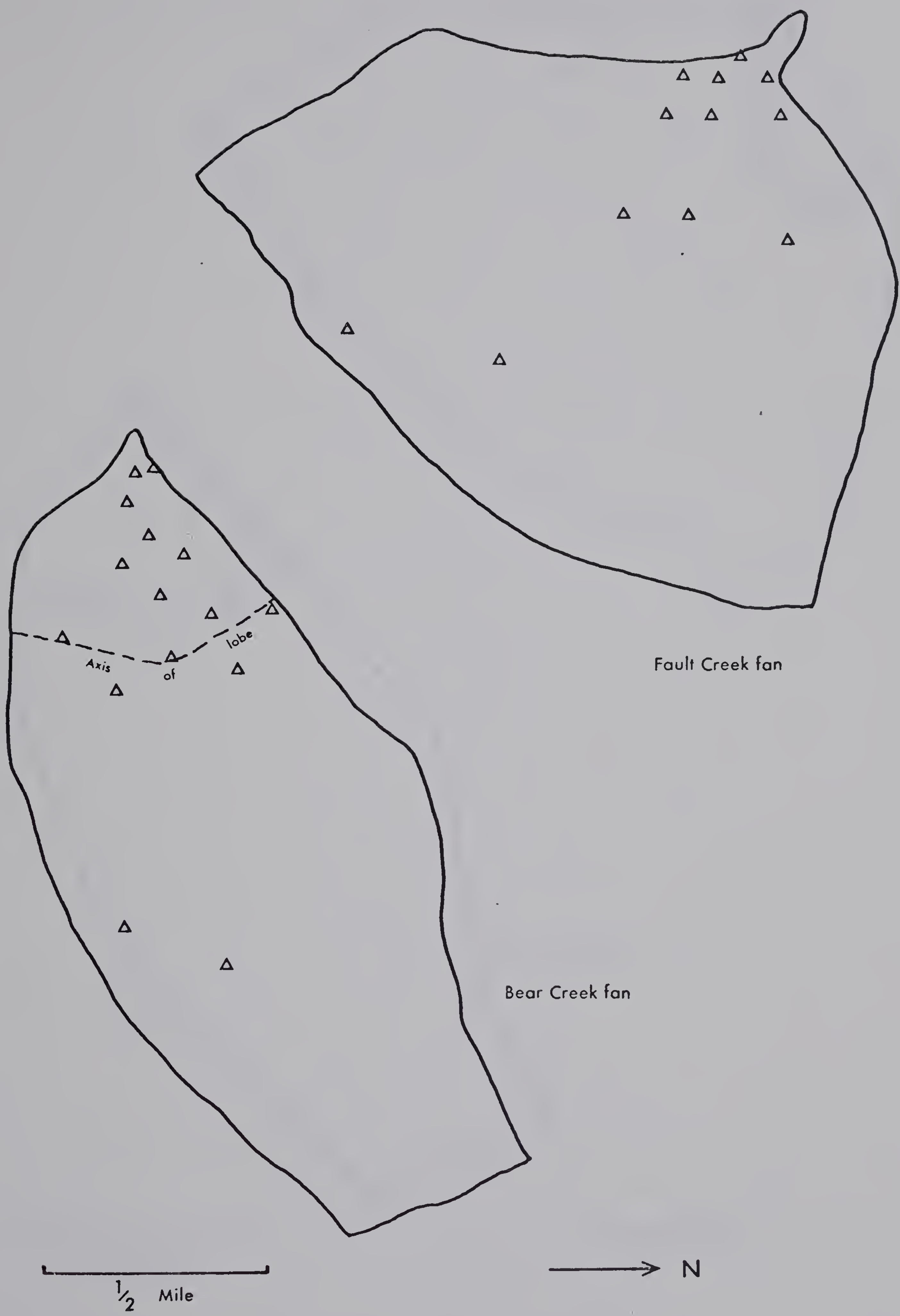


FIGURE 15 : CM pattern locations - Mudflows

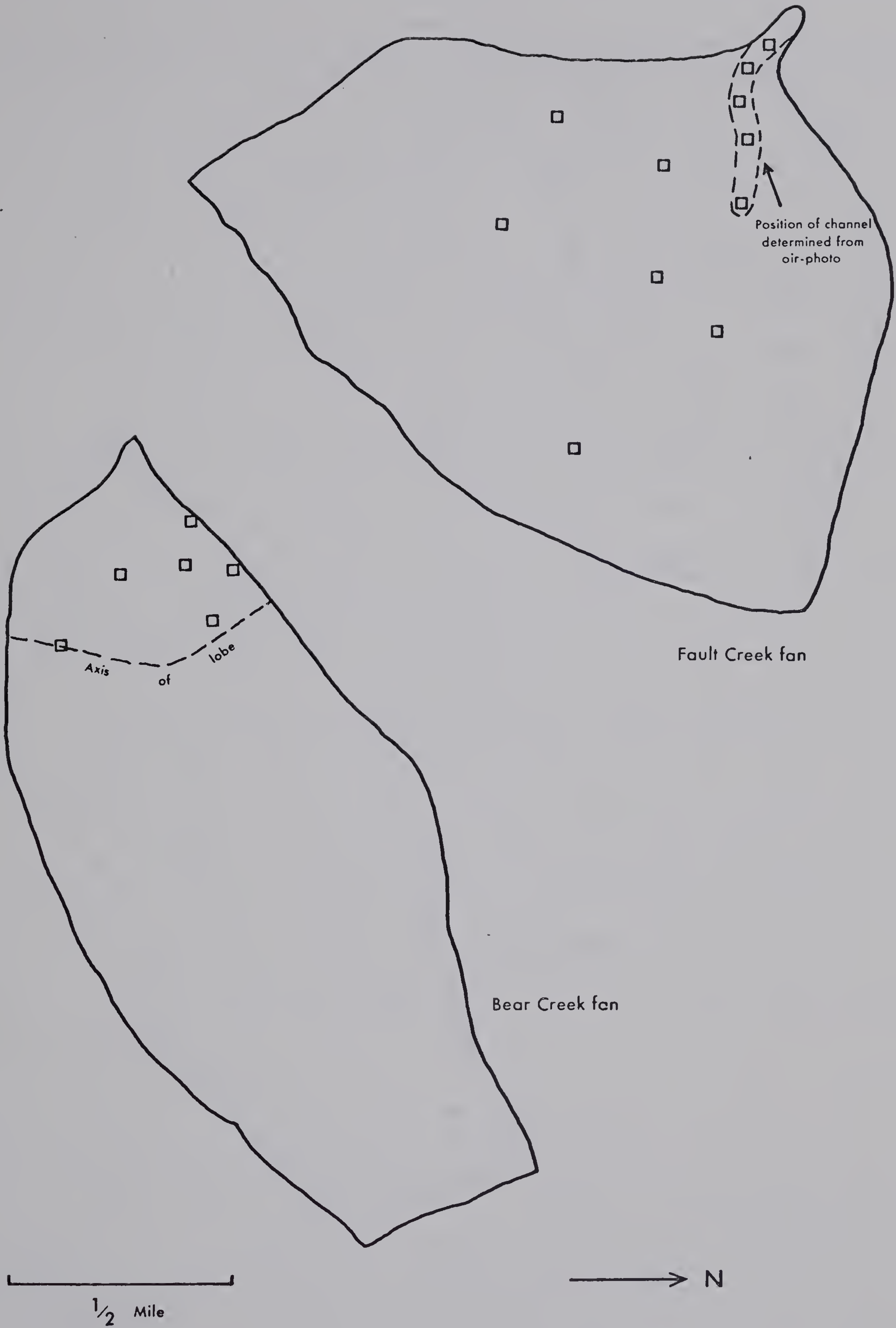


FIGURE 16: CM pattern locations - PQ segment
(lateral accretion deposits)

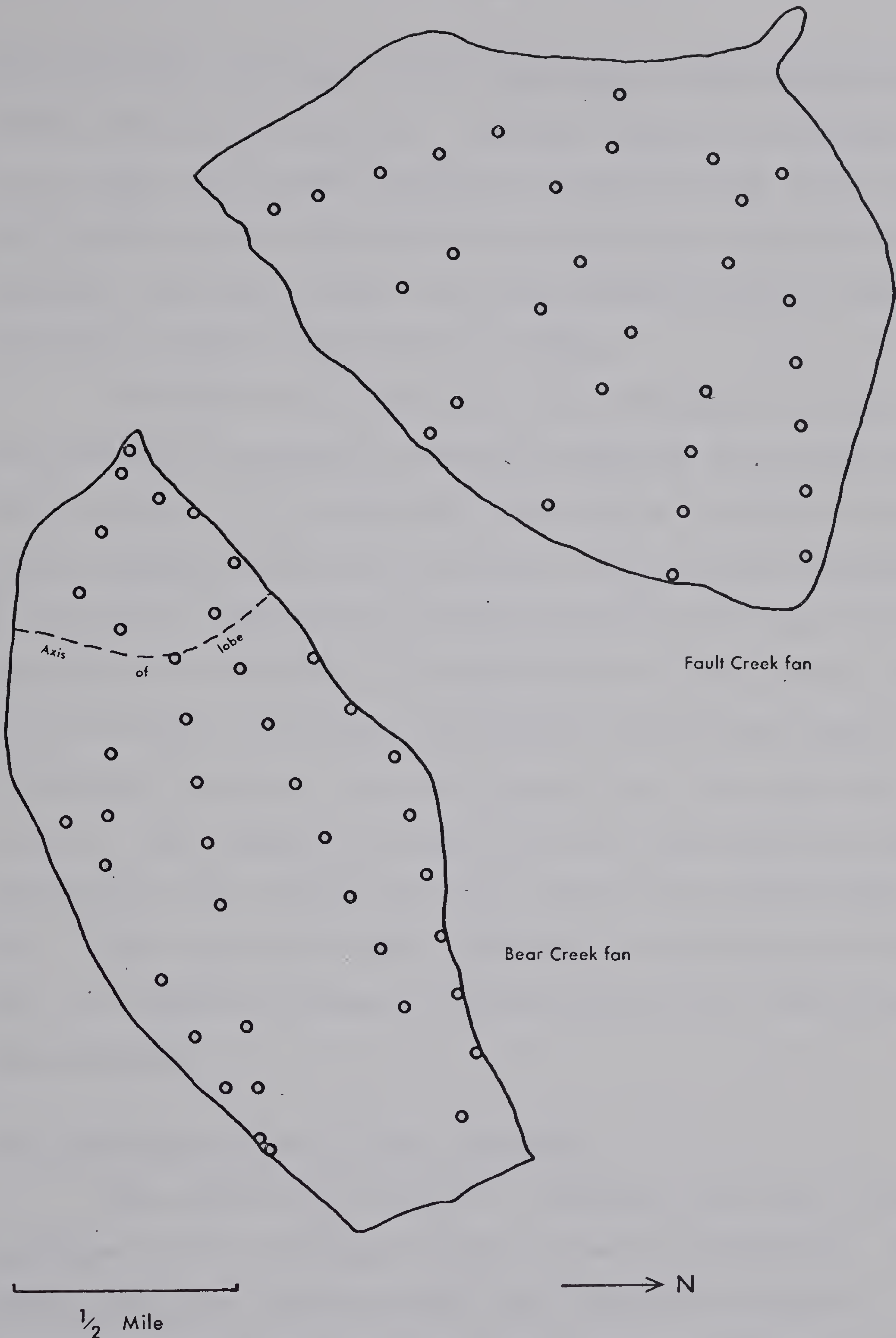


FIGURE 17 : CM pattern locations - RS segment (overbank deposits)

which possibly accounts for RS locations at the fanhead where active channels are present. However, neither Bear Creek nor Fault Creek fans exhibit defined channels towards their toes. The presence of RS locations in this area may therefore be anomalous, but since only surficial sediment samples were collected, channels may exist at depth.

It should be stressed that the Passega/Bull model is not generally accepted as a proven technique of process differentiation. It is dependant upon accurate sampling from single sedimentation units, and the two parameters measured do not give a complete description of the grain-size characteristics of a sediment. Interpretation of the various patterns is fairly subjective, and errors would arise where a number of different sediments could lie in the same CM pattern. For example, a sample of till, when plotted, could conceivably fall within the long, rectilinear mudflow pattern. This technique should therefore be used only in support of a working hypothesis derived empirically from other observations.

Areal characteristics of fan sediments

The choice of an index to represent the areal characteristics of fan sediments proved to be very difficult. The median and Trask sorting coefficient are not efficient indices, and the four Folk and Ward statistics were unobtainable. Non-dimensional indices such as $\frac{\text{clay-silt\%}}{\text{sand-gravel\%}}$ are

difficult to interpret, and so the writer subjectively decided to use percentages of clay and of sand per sample.

The manual construction of isoline maps from discrete sample points involves a moderate amount of subjective interpolation. To overcome this, all data was coded, transferred to punched cards, and processed by SYMAP 5, a mapping program obtained from the Laboratory for Computer Graphics and Spatial Analysis, Harvard Centre for Environmental Design Studies. Input was in the form of x and y coordinates, fixing the sample point in space, and a z value, being the magnitude of the experimental variable at that point. Four maps were produced, for the percentage of clay and of sand per sample for both Bear Creek and Fault Creek fans (Figures 18 and 19).

Interpretation of the isoline maps is extremely difficult. No definite patterns emerge, and any hypothesis based on the local isoline irregularities are highly speculative. Quartic trend-surface maps were also produced for clay and sand percentages per sample for Bear Creek and Fault Creek fans, but yielded patterns equally obscure.[1] As an example, the quartic trend surface map and residuals for clay percentages of Bear Creek fan samples are shown in Figure 20. If one accepts the assumption that a fluvial system should produce some form of ordered areal sediment pattern,

---

[1]The trend surface program used was by Spitz, O'Leary and Lippert, 1964 (see bibliography).

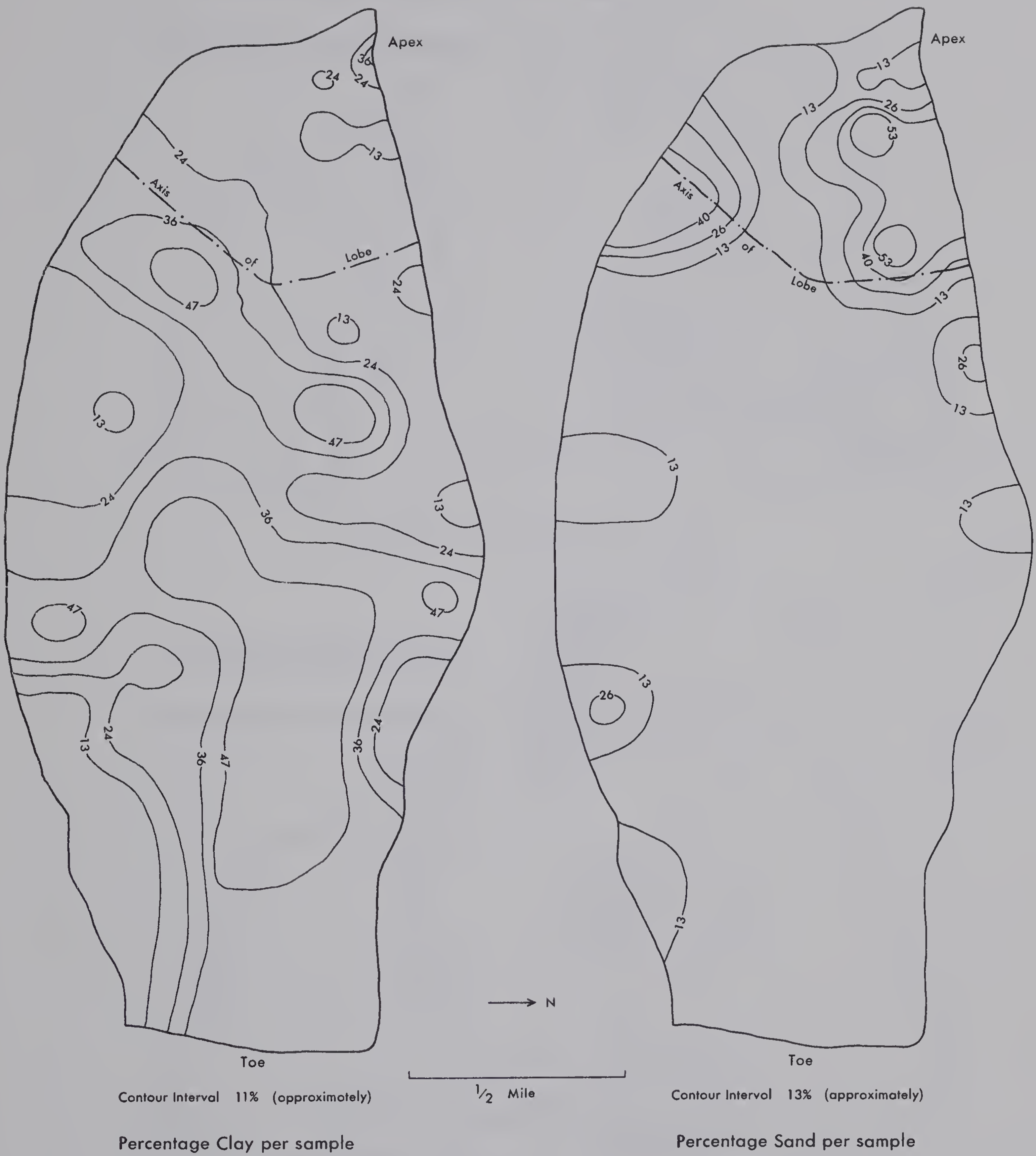


FIGURE 18 Grain-Size Isoline Maps for Bear Creek fan

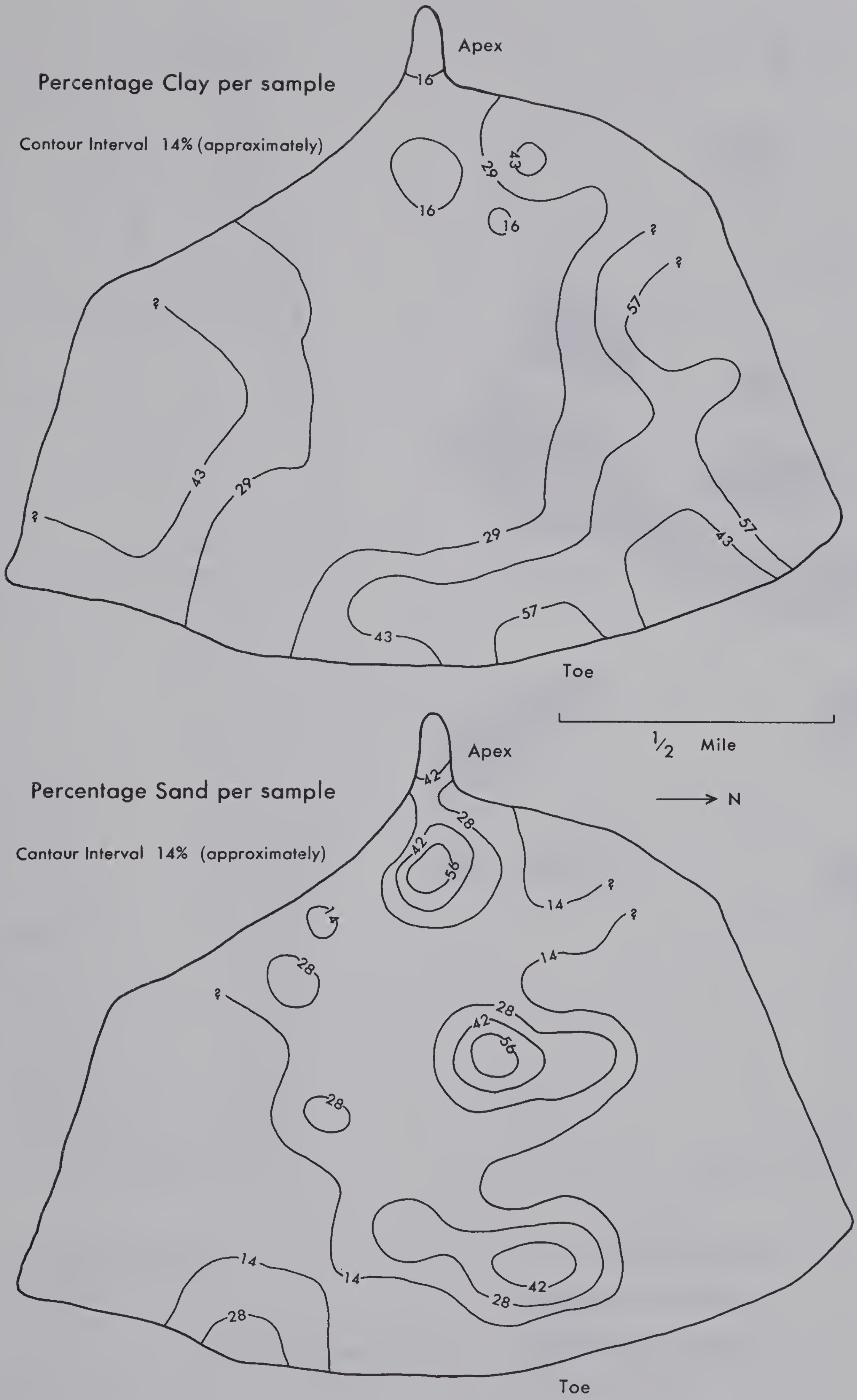


FIGURE 19 Grain-Size Isoline Maps for Fault Creek fan

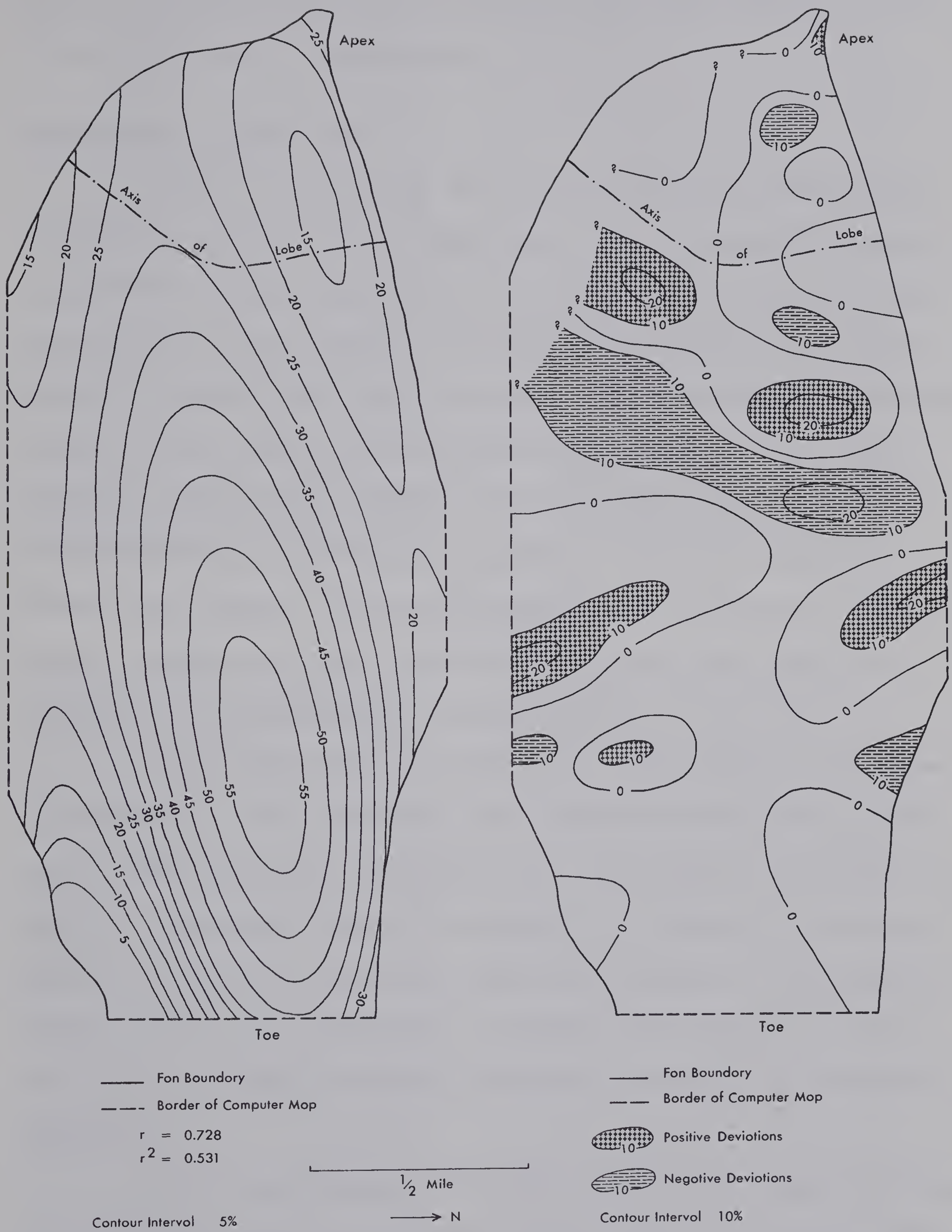


FIGURE 20 Fourth Order Trend Surface and Residuals for Clay Percentages of Bear Creek fan samples

then the isoline and trend-surface maps may indicate a non-fluvial process of deposition.

Sedimentary sequences

Plate 7 shows some of the exposures of sedimentary succession noted in the study area. Most creeks had poorly stratified gravels exposed at the apex (Plate 7:A and 7:B), while Slide Creek fan had a buried soil horizon above six feet of coarse gravel and boulders in a finer-grained matrix (Plate 7:C). Most of the gravels are angular, and interstitial cavities are filled with finer material. The poor stratification, angularity of gravel, and finer-grained matrix all suggest successive mudflows of differing competence. Layers of sand noted in the field could have been deposited from subsequent stream flow.

Other exposures of sedimentary succession are shown in Figure 21. All sections show interdigitation of gravel, sand, sandy-silt and clay-silt, all with organic streaks or layers. These may also be explained in terms of successive mudflow activity, with some minor re-working of sediment by fluvial action near the apex, although the layers of clay-silt could possibly indicate vertical accretion of overbank deposits.

Data from boreholes driven at the time when the fans were a likely location for the resettlement of Aklavik indicate much coarser material near the apex of Willow Creek fan


A: Gravels--Willow Creek fan apex


C: Buried soil horizon--Slide Creek fan apex


B: Gravels--Jimmy Creek fan apex


D: Recent mudflow--Willow Creek

Plate 7

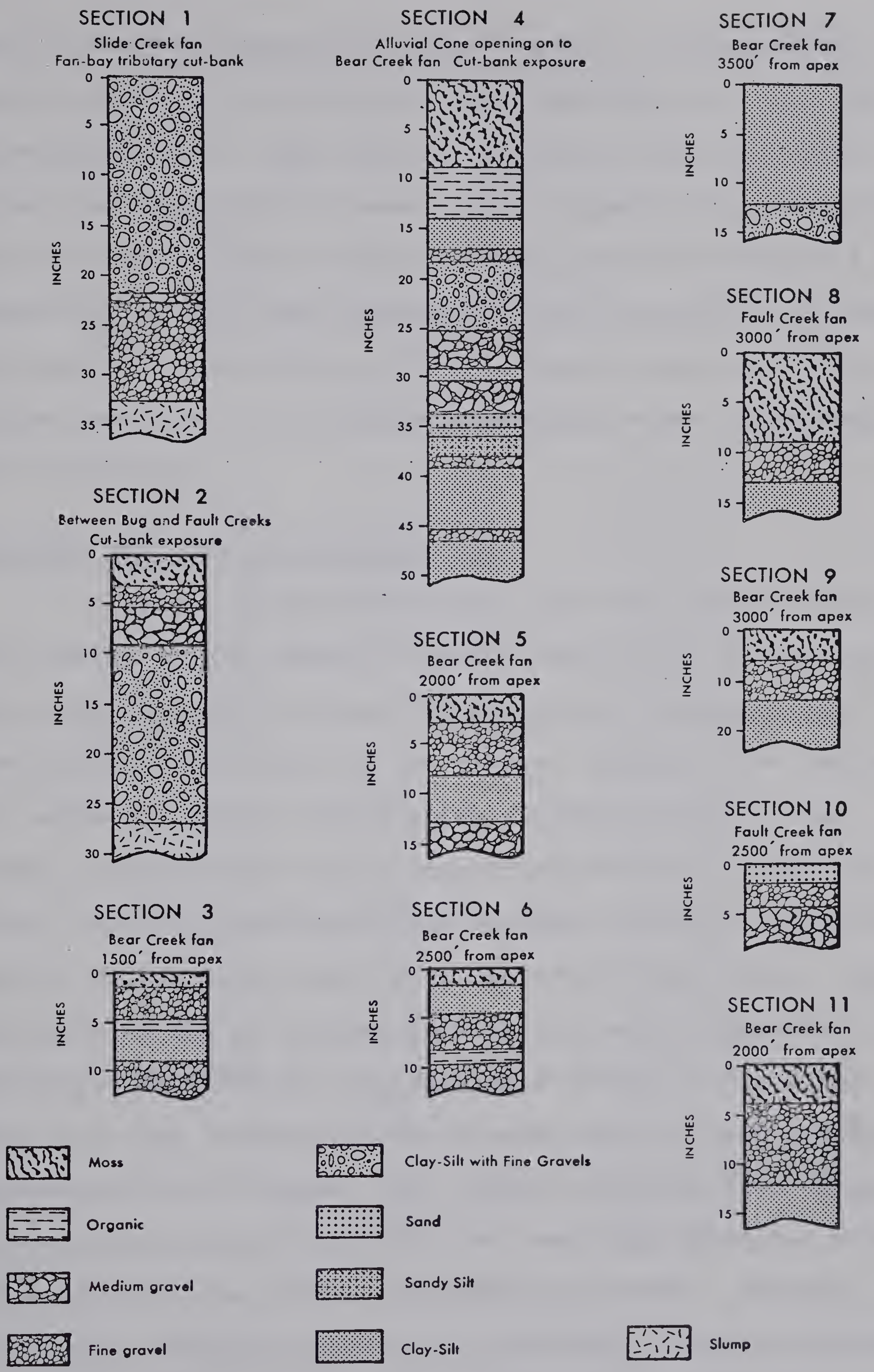


FIGURE 21: Exposures of Sedimentary Succession

than at the toe (Figure 22, Holes 3 and 1). The surface sample collected by the writer from approximately the same location as Hole 3 was composed largely of clay-silt with 11 per cent by weight of sand. This compares favourably with the sediment depicted in the surficial part of Borehole 3. Deposition of the finer material at the toe could be by vertical accretion, but as only three boreholes were driven on Willow Creek fan, the incomplete coverage makes interpretation intuitive.

Sediment analysis conclusions

A visual inspection of the grain-size curves of fan and mudflow samples showed a strong similarity, a relationship supported by the ranges of median and Trask sorting coefficient values for the two groups. However, the coarsest fan sediment formed a distinctive grouping of grain-size curves, separate from those resembling mudflows. This provided a working hypothesis that although mudflow samples are present on the fans, some other process is also active. Application of the Bull/Passega CM pattern model supported the hypothesis that mudflow activity is a factor in fan formation, but also suggested that lateral accretion and overbank deposition may be common. The sample locations from these three groups were plotted, but the resulting zonations were not characteristic of the respective processes. However, the mudflow samples tended to be clustered around fan apices, and overbank deposits were relatively evenly distributed

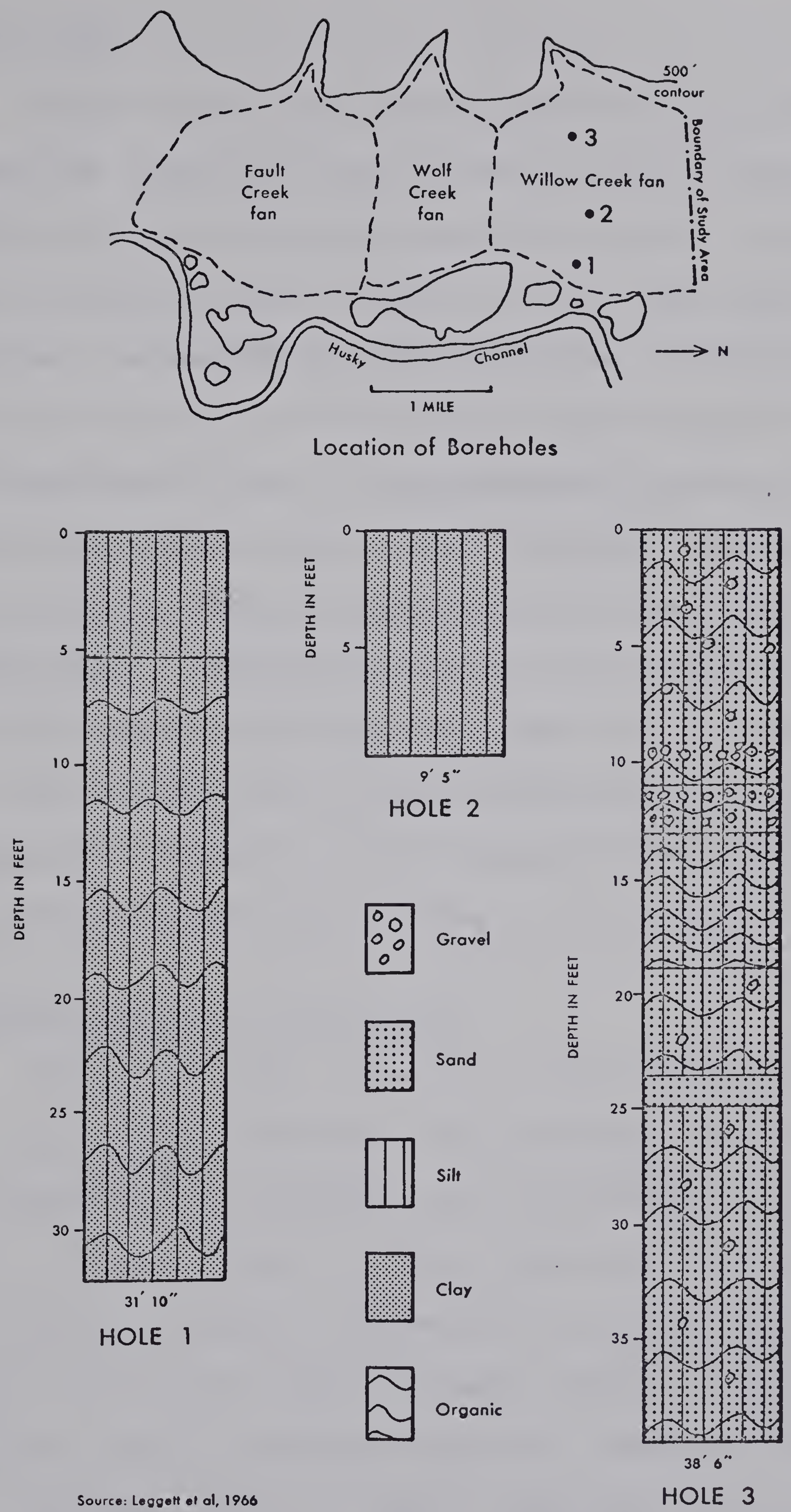


FIGURE 22: Borehole profiles from the Aklavik fans

over the fans.

Isoline and trend-surface maps of clay and sand percentages per sample for Bear Creek and Fault Creek fans yielded a confused picture, and do not really support the CM pattern interpretations. However, data from exposures of sedimentary sequences and from boreholes, although giving incomplete coverage over the fans, tend to agree with the basic hypotheses, that is, that mudflow activity in the fan-head area may play a part in fan formation, with some lateral accretion by active channels near the fan apex and overbank deposition distributed evenly over the major portion of the fan immediately below the apex zone. In order to relate the feasibility of these conclusions to the climate and geomorphic response of the Aklavik area, a discussion of the probable hydrologic regime is necessary.

Hydrologic regime of the Arctic

Much geomorphic research in the Arctic has concentrated on glacial processes and morphology, with the result that relatively few records exist pertaining to fluvial action. Kerfoot (1969, p. 295), working at the northern end of the Mackenzie Delta, claimed that running water was not an active geomorphic agent on Garry Island, due to low precipitation, small catchment areas and continuous vegetation cover. Rudberg (1963, p. 146-7) observed that stream action during snow-melt was not particularly important on Axel Heiberg Island, and that most fluvial activity was due to

intense summer rainstorms and the effect of a high permafrost table, scanty vegetation, and a shale bedrock with large areas of low permeability. Thus, run-off tended to flood alluvial fans which were present in the area.

Describing the Mackenzie Delta in general, Mackay (1963, p. 43) noted that the effectiveness of total precipitation (snow and rain) is concentrated in the four months from June to September. A great amount of stream erosion is accomplished by flood waters fed from melting snow and thawing soil in late May and early June. Further north, at Resolute, Cook (1967, p. 267) maintained that the spring 'freshet' or flood was the main agent of removal for most rock waste. Rapid melting causes the disappearance of snow in two or three weeks, resulting in 90 per cent of the run-off and high stream velocities (p. 265). Heavy summer rains (from one or two storms) produce rill-wash and miniature fans and deltas which are washed away next spring.

Similarly, Czeppe (1965, p. 144), working in Spitsbergen, emphasised the spring sheet-flood caused by melting snow, which results in silt-laden water occupying all the 'indentures of the (sloping) surface'. By the end of the snow-melt period, Czeppe maintained that sheet-flood changes into linear flow. Czeppe concluded that the activity of rain-water was less important than that of meltwater; that the greatest intensity of flow was achieved while the ground was still frozen; and that dispersed flow or sheet-flood

dominates over linear flow (p. 146).

Climatic factors, therefore, considerably influence the effectiveness of fluvial activity in the Arctic, determining the amount and duration of spring snow-melt and the number and intensity of summer rainstorms. Climatic data for the Aklavik area has already been presented in Figure 5, and it can be seen that in May and June, when temperatures first rise above freezing point, an average of 4.32 inches of water equivalent is present in the form of winter snow cover. However, Aklavik itself, situated on the delta, is in the rain-shadow of the Richardson Mountains which lie further to the West. The orographic effect of the Richardson Mountains possibly causes greater snowfall over the Aklavik Range, and increases the likelihood of summer rainstorms.[2] The combination of spring snow-melt and early summer rainstorms produce rapid run-off over a frozen surface, resulting in a spring flood or "freshet" of the type described by Cook (1967).

The presence of the permafrost table plays an important part in preventing the infiltration of water into the fans. During fieldwork, permafrost was encountered at 6"+, and the actual depth at each sample site is recorded in Appendix B. As the permafrost slowly melts in response to higher summer temperatures, the moisture content of the active layer increases to saturation point. This environment must be conducive to mudflow development, especially

[2]Pers. comm., J. K. Fraser, Ottawa.

where slopes are steep.

The months of May and June would therefore be the period of maximum mass-movement activity, with the permafrost table very close to the surface forming a lubricated plane down which flowage of saturated material could take place. During this period, large amounts of sediment are possibly supplied to the valley floors by mudflows, causing temporary debris dams, and rapidly decreasing the water:sediment ratio. The resulting flow on to the fans could be highly fluid or viscous, dependent on the amount of sediment supplied by mountain mudflows and other forms of mass-wasting. Field evidence exists for flows of this type, for example, the presence of a six foot high boulder in Wolf Creek, capped with a considerable amount of coarse debris (Plate 8:A). Further downfan, below active apices, such flows tend to spread out, as suggested by actual field observations of large areas of sluggish, slow-moving, muddy water, and extensive spreads of fine-grained sediment (Plate 8:C).

Despite the importance of spring snow-melt, it should be remembered that the climate of the Aklavik area is otherwise predominantly semi-arid. This is reflected in the presence of considerable evaporite deposits which strongly resemble layers of 'caliche' found in the arid southwest of the U.S.A. This white encrustation appeared to be typical of deserted washes, and was very noticeable in vertical gravel exposures at depths of up to one foot. A sample of


A: Boulder capped by flood debris--Wolf Creek


B: Summer snow banks--Bear Creek


C: Vertical accretion from overland flow--Jimmy Creek

Plate 8

the evaporite crust was taken, and on analysis proved to be composed largely of Calcium and Magnesium Sulphates with a slight trace of Chlorides.[3] These salts originate in the marine sediments of the Aklavik Range and indicate the rapid loss of moisture into the dry air subsequent to peak discharge. However, there was considerable flow from active channels throughout the duration of field work, and some flow is probably present for the rest of the summer, judging by the size of the snow banks in the head-waters (Plate 8:B, taken on June 28th, 1970).

This discussion of the hydrologic regime of the study area suggests that the climatic features of permafrost combined with spring snow-melt, peculiar to the Arctic, result in a combination of processes. Mudflows may occur on steeper slopes, while the spring flood carries away much of the load supplied to the valley floors. This 'freshet' would at first be confined by the banks of the active channel, causing lateral accretion on slip-off slopes. With increasing discharge, bankfull stage would be reached, and despite the slight fanhead incision noted earlier, overbank flow would result in the deposition of fine material in the fanhead zone. Downfan, below the active apex, the unconfined flow would also spread out, decreasing in velocity, and slowly move towards the fan-toe, with infiltration prevented by the

---

[3] The analysis was performed by Prof. J. A. Robertson of the Department of Soil Science, University of Alberta.

presence of the permafrost table. The stable vegetation mat, present over most of the fan, would cause sediment entrapment resulting in the layers of clay-silt with streaks of organic matter noted in many exposures of sedimentary succession. Mudflows affecting the fanhead zone could be caused by unusual climatic or geomorphic factors, such as deep winter snow cover, heavy rainfall during the spring snow-melt period, and great mudflow activity on drainage basin slopes, which, by temporarily damming the stream at a number of points could generate excessive flood water charged with large amounts of coarse and fine sediment. Mudflows are therefore suggested as agents both of sediment supply and of fan formation. The discussion which follows assesses the importance of mudflow activity in the study area in the light of available literature on this subject and the writer's own field observations.

Mudflow activity in the study area

Mudflows have not been widely reported in Northern Canada (Bird, 1967, p. 182) but Sigafoos and Hopkins (1952) claim that they are characteristic features of certain undisturbed tundra areas. Rudberg (1963) noted mudflows with typical levees on the steeper slopes of Axel Heiberg Island in the High Arctic, while Kerfoot (1969) claims that in the Mackenzie Delta the mudflow is an ubiquitous feature of permafrost areas underlain by unconsolidated sediments containing variable quantities of segregated ground ice (p. 185). Working on Garry Island, Kerfoot even suggested that

the three-fold mudflow classification by Sharpe (1938), that is, semi-arid, alpine, and volcanic, should be extended to include a fourth--the arctic type--intimately related to specific permafrost conditions (Kerfoot, 1969, p. 186-7). Kerfoot also maintained that all mudflows in the Mackenzie Delta were produced by seasonal thawing of the permafrost.

Some twenty miles northeast of the Aklavik fans, in the Canoe Lake area, Lambert (1968, p. 6) described tundra mudflows as 'common'. He noted previous mudflows in different stages of revegetation all around the lake and on several steep slopes bordering the creek south of it. Lambert claimed that these mass movements are a result of surface heaving during the autumn in which the vegetation mat is separated from the mineral soil. During the following spring thaw, the saturated soil flows downslope along defined channels leaving islands of vegetation scattered throughout the mudflow. Lambert also suggested that in many cases mudflows resulted from the oversteepening of slopes by solifluction or by erosion at the base of a cut-bank.

The presence of mudflows on the slopes of the Aklavik Range has briefly been noted by Fraser (1956, p. 21) and Henoch (1960). During reconnaissance, however, the author made a study of mudflow occurrence in the mountain area and many mudflow sediment samples were taken. The morphology of these mudflows was comparable to that of similar features described and photographed by Kerfoot (1969) although mudflow

activity on Garry Island is mainly in response to marine erosion and the melting of segregated ice masses (Kerfoot, 1969). Causes of mudflow initiation in the Aklavik study area may be similar to the mechanism proposed by Lambert (1968), judging by a number of islands of vegetation, surrounded by mudflow deposits. On the other hand, these may represent divergence of flow either side of an area of vegetation, rather than the erosion, transportation, and deposition of a vegetation mat. Mudflow tracks were noted in all drainage basins, and were of the type described by Prior et al. (1968) as 'composite mudflows', that is, having a source area (the bowl-slide zone), a well defined flow track, and a hummocky depositional toe zone (Plate 9). Plate 9:A shows an excellent example of the type of mudflow found in the study area. Mudflows were noted in all stages of revegetation and flow probably recurred along each track following a cyclical pattern. Recent mudflows still retained a rippled mud surface, though subsequent rill action was indicated by local incision (Plate 10:A and B). Older mudflows formed a distinctive ecological unit, being colonised by fireweed (*Epilobium augustifolium*), buckwheat (*Polygonum alpinum*), ragwort (*Senecio yukonensis*) and many rapidly growing grasses. It was therefore relatively easy to identify mudflow tracks in the mountain area largely from their botanical composition, but such distinctive plant associations were not observed on any of the fans.

To determine whether a particular slope angle was

A: Multiple mudflow tracks--Tundra Creek

B: Old mudflow between Bear and Tundra Creeks

C: Mass-movement lobe between Bear and Tundra Creeks

Plate 9

Plate 10: Recent mudflows in Willow Creek

critical for mudflow development, the slope angles of thirty-six mudflows were measured using an Abney Level. Readings were taken from the toe to the source area (bowl-slide zone) and the results are shown in Table 5, indicating a fairly normal distribution with a mean mudflow slope of 17°00', median of 17°25' and standard deviation of 5°00'. Thus, slope instability appears to occur within a relatively small range of values, 7° being the lowest angle recorded. High angles of slope failure are not present because few slope angles steeper than 30° exist in the study area, other than bare rock faces or the scree slopes at their feet.

The grain-size curves of mountain mudflow samples have already been presented (Figure 13). In general, the mudflows are composed of a few large particles in a matrix of clay and silt. It is possible that the clay-silt is derived from the mantle of till on the drainage divide, while the large particles represent bedrock picked up during mudflow movement, or stones washed out from the till. Percentages of sand, silt, and clay are available for seventy-two soil samples taken from the crest of the Aklavik Range between Mt. Gifford and Mt. Goodenough.[4] Although it was not certain whether all these samples were till-derived, the clay and silt percentages were added, to determine to what extent the soil, as the probable source of much mudflow

---

[4]Unpublished data--Dr. R. Bryan, Department of Geography, University of Alberta.

TABLE 5

A SAMPLE OF MUDFLOW LOCATIONS AND SLOPE ANGLES

Location	Angle
Bear Creek	17°50'
"	19°20'
"	22°05'
"	21°30'
* Cone A	13°55'
"	15°40'
"	10°30'
* Cone B	14°30'
"	11°35'
* Cone C	13°40'
"	9°05'
"	11°45'
* Cone D	11°50'
"	7°05'
* Cone E	25°40'
"	23°50'
* Cone F	26°15'
"	18°00'
"	21°10'
Between Fault and Bug Creeks	19°40'
"	16°50'
"	20°15'
"	18°40'
"	10°20'
Wolf Creek	13°30'
"	12°30'
"	18°00'
Fault Creek	23°00'
"	15°15'
"	19°50'
Bug Creek	17°00'
"	14°25'
"	9°30'
Willow Creek	18°55'
"	22°30'
"	25°00'

Mean	16°57'
Median	17°25'
Standard Deviation	5°00'

*Cones A to F are located along the mountain front between Bear Creek and Tundra Creek.

sediment, was rich in fine-grained material. The resulting values had a mean of 76.65 per cent and standard deviation of 12.33 per cent. Analysis of the grain-size percentages of fan samples (Appendix D) shows that they are also rich in fine-grained material and in only nineteen cases was the percentage of clay greater than that of the silt.

During spring snow-melt, the upper layers of the soil on the crest of the Aklavik Range must become saturated due to the melting of the permafrost. Unfortunately, only five slope angles were measured on the upland tundra, located above Bear Creek, yielding values of 12°, 12°30', 11°, 11°30', 9°30', and 9°30'. Although these figures refer to one small area of the upland surface, they do show that at least in that locality, slopes are steep enough to induce mass-movement of saturated sediment, producing lobes similar to that shown in Plate 3:B. Thus fine-grained sediment is continually being moved downslope towards the pronounced break of slope existing between the upland surface and the incised valleys (Plate 2:A and B). As this sediment reaches the steeper valley sides, the combination of fine-grained material, high water content, and high angle slopes must induce mudflow activity. It is therefore suggested that the upland soil may well be a source of much of the clay-silt present in mountain mudflows from the study area.

During reconnaisance, a number of mudflow dams, in various stages of breaching, were noted in the valleys above

the fans. One such dam, observed in Bear Creek, may have been fairly recent, as a five foot high waterfall was actively cutting back into the debris. Upstream from mudflow dam remnants the water was clear, but downstream a high clay-silt content was reflected in the mud-brown colour of the water.

Although mudflows were commonly noted on steeper slopes within the mountains, there was no evidence of mudflow tracks or levees on the fans themselves, nor was there any sign of plant associations characteristic of recent mudflow deposition. However, the prominant lobe near the apex of Bear Creek fan (Plate 4 and Figure 8) and the less pronounced break of slope on Tundra Creek fan (Figure 8) may be morphological indications of mudflow activity.

Data cited earlier suggests that the fine-grained sediment occurring randomly over the fans (Figure 17) may have been deposited by overbank flow. The clay-silt may have originated from the upland soils, having been transported to the valley floors by mudflows. Leggett and Brown (1956) and Leggett et al. (1966) however, put forward the hypothesis that the fine-grained material represents coarser sediment that has been comminuted by the combined action of freeze-thaw and organic acid breakdown. The discussion which follows evaluates this hypothesis in the light of recent laboratory experiments.

Comminution of sediment by freeze-thaw and organic breakdown

There is no conclusive experimental evidence that

freeze-thaw generates a clay-silt rich weathered fraction (Tricart, 1956; Fraser, 1959; Wiman , 1963; Potts, 1970; Keeble, 1971). However, to evaluate the hypothesis put forward by Leggett et al. (1966), some samples of fan sediment, collected from the study area, and previously analysed for grain-size characteristics, were tested under laboratory conditions.

In order to ascertain the effect of organic breakdown on the sediment samples, some peat, taken from the fans, with pH values ranging from 7.0 to 5.5, was digested at 90°C in 0.5 normal NaOH (pH of 8.6). The resulting solution, composed of Humic/Fulvic acid and Sodium Hydroxide in unknown proportions, had a pH of 8.0. The supernatant fluid was decanted and filtered ready for laboratory use.[5] Ten samples, each ranging in particle size from 0.002 mm to 2.0 mm, were subjectively chosen and dry-sieved through a 0.063 mm mesh to separate out most of the clay-silt fraction, which was discarded. Each sand-gravel fraction which remained was quartered into four equal parts, the first of which was placed in a plastic tub, covered with distilled water, sealed to prevent evaporation and stored as a control. The second quartered fraction was covered with the organic solution, sealed, and also put aside as a control. Fractions three and four were immersed in distilled water and organic solution

---

[5]This extraction of Humic/Fulvic acid was based on a method outlined by the Soil Science Department at the University of Alberta.

respectively and subjected to fifty freeze-thaw cycles. Wiman (1963) and Potts (1970) have suggested that neither the length nor intensity of freezing are as important in the production of weathered material as the number of times the temperature crosses the freezing line, or the rate at which freezing takes place. As a result, the temperature of a deep-freeze unit was set at -22°C (Raiche, 1950, p. 12) and the twenty samples allowed to freeze for approximately sixteen hours. After this time the tubs were removed and allowed to thaw for approximately eight hours. This sequence was repeated until fifty cycles had taken place.

The environment of freezing, that is, complete immersion in water, may appear to be unnatural, but in fact reproduces fairly exactly the conditions prevailing on the fans during the summer months. The thawing of the permafrost moistens the active layer, to which is added the spring snowmelt and rainfall from summer storms. During late spring and early fall, when freeze-thaw cycles are most numerous, the ground surface is, therefore, fairly well saturated.

After the fiftieth cycle, the sediment in the tubs was transferred to glass beakers, which were placed on a hotplate at 200°F. Five ml. of 30 per cent H_2O_2 was added to each beaker, to digest all humic material. Frothing was extensive from those beakers containing the organic solution, but H_2O_2 was added drop-wise until frothing ceased. All forty samples, both control and freeze-thaw groups were then

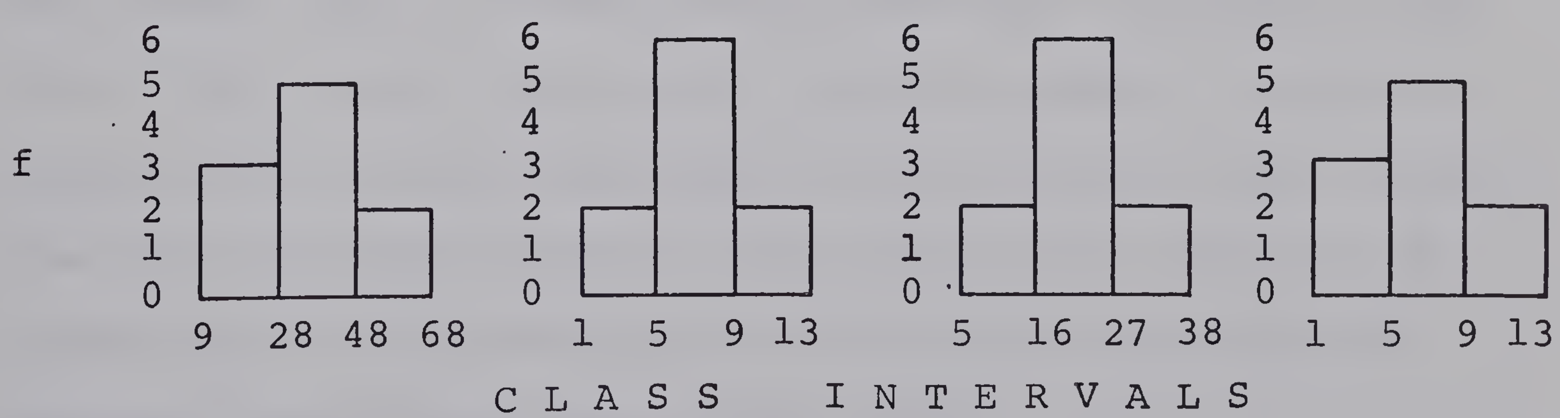
wet-sieved through a 0.063 mm mesh. The fines passing through, and the sediment retained by the mesh were oven-dried separately at 250°F, and weighed. The fines were calculated as a percentage of the quartered sample weight, and the results are shown in Table 6. The four groups had relatively normal distributions, allowing parametric statistical tests to be performed on them.

TABLE 6

CLAY-SILT PERCENTAGES PRODUCED BY FREEZE-THAW AND ORGANIC BREAKDOWN

Sample No.	Freeze-thaw (organic)	Freeze-thaw (water)	Control (organic)	Control (water)
1	9.686	4.966	5.450	1.635
3	30.079	12.327	15.803	6.430
6	34.225	7.843	22.780	11.289
11	31.463	10.820	18.447	12.043
24	17.902	5.264	7.306	3.460
120	47.983	5.386	26.057	6.601
142	54.815	7.497	26.993	7.560
143	37.317	7.448	18.488	6.390
151	53.304	7.795	36.789	2.319
160	53.984	4.709	29.013	6.658
	$\bar{x}$ = 37.076	$\bar{x}$ = 7.406	$\bar{x}$ = 20.713	$\bar{x}$ = 6.539

HISTOGRAMS SHOWING NORMALITY OF SAMPLE DISTRIBUTIONS



However, application of the F ratio test showed that the variance due to interaction was significant at the 99 per cent probability level. As interpretation of the other terms was therefore difficult, further analysis of variance was abandoned (Hope, 1967), and the t test was used instead. The t statistic was calculated from the formula

$$t = \frac{\left|\bar{X}_i - \bar{X}_j\right|}{\hat{\sigma}\sqrt{\frac{1}{n_i} + \frac{1}{n_j}}}$$

where $\bar{X}_i$ and $\bar{X}_j$ are the sample means; n_i and n_j are the number of observations in each sample; and $\hat{\sigma}$ is the best estimate of the population standard deviation, calculated from the equation

$$\hat{\sigma} = \sqrt{\frac{(n_i-1)S_i^2 + (n_j-1)S_j^2}{n_i + n_j - 2}}$$

S being the sample standard deviation.

The results are shown in Table 7. In each case the degrees of freedom are $n_i + n_j - 2 = 18$. At the 99 per cent confidence level, all of the computed t values are significant, except the t statistic which compares the means of the freeze-thaw (water) and control (water) samples. Although these results are not conclusive, they indicate that freeze-thaw combined with breakdown from organic or chemical compounds may be more effective in producing clay-silt rich sediments than freeze-thaw action alone.

TABLE 7

COMPARISON OF FREEZE-THAW AND ORGANIC SAMPLE MEANS

The matrix is of values for Student's t, with 18 degrees of freedom.

	Freeze-thaw (organic)	Freeze-thaw (water)	Control (organic)	Control (water)
Freeze-thaw (organic)	-	6.274	2.970	6.373
Freeze-thaw (water)	6.274	-	4.424	0.676
Control (organic)	2.970	4.424	-	4.592
Control (water)	6.373	0.676	4.592	-

At the 99 per cent confidence level, with 18 degrees of freedom, the tables give t = 2.552

The research methods outlined above can be criticised from a number of viewpoints, in particular regarding the organic solution used in the experiment. The proportions of Humic/Fulvic acid and Sodium Hydroxide were unknown, but judging from the pH value of 8.0, the liquid was alkaline. In the absence of any record of laboratory experiments to relate freeze-thaw and organic breakdown, this pilot study may provide a basis for further research. The results should be interpreted with care, in the light of the small number of freeze-thaw cycles, roughly equivalent to two Aklavik winters (Leggett, et al., 1966), and the uncertainty regarding the exact effect of the "organic" solution.

Summary

The results of the sediment analysis proved to be difficult to interpret. A visual comparison between grain-size curves of fan and mudflow samples, the latter taken from steep, drainage-basin slopes, showed considerable similarity between the two groups. Some of the median and Trask sorting coefficient values were also comparable. Application of Passega/Bull CM patterns, although an unproven technique, suggests that fan samples can be classified into one of at least three groups--lateral accretion, mudflow, and overbank deposits. When locations of these groups were plotted, no definitive pattern emerged, although mudflow samples tended to be clustered around fan apices and overbank deposits were relatively evenly distributed over the fans. Isoline and quartic trend-surface maps of grain-size percentages over Bear Creek and Fault Creek fans yielded a confused, complex pattern and do not support the CM interpretations. However, the few sedimentary exposures available in the study area tend to agree with the basic hypothesis of a combination of mudflow and fluvial activity.

Analysis of climatic data for the Aklavik area, combined with available descriptions of the hydrologic regime of the Arctic, suggests that a spring flood or 'freshet' is characteristic of the run-off in the study area. This hypothesis is supported by field observations and provides an explanatory model for the distribution of fan sediments. A

combination of climatic and geomorphic conditions may lead to mudflow deposition in the fanhead zone, otherwise lateral accretion occurs in active channels, with vertical accretion of overbank deposits all over the fan.

Mudflows are common on drainage basin slopes, and are active in transporting clay-silt rich material from the upland tundra to the valley floors. Mudflow dams may be formed but are rapidly breached by flood waters eroding the fine-grained mudflow sediment, resulting in the vertical accretion of overbank deposits downfan. Laboratory experiments indicate that further comminution of fan sediment in situ may take place in response to a combination of freeze-thaw action and organic breakdown. This supports the hypothesis put forward by Leggett et al. (1966). However, in relation to the study area, breakdown of fan sediment has to occur during the geologically brief period between initial deposition and burial of the sediment by subsequent accretion, which may negate the effects of mechanical weathering.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The basic purpose of this study was to determine the principle processes of alluvial fan formation in the Aklavik area. It was also hoped that the areal variation, if any, of these processes, could be assessed. The results of previous work in the study area suggested that the fan sediments were clay-silt rich, and this hypothesis was to be tested and some explanations proposed.

Field-work was designed to investigate three aspects of fan geomorphology. Longitudinal fan profiles were surveyed, surficial sediment samples were collected from both the fans and from steep-angle mudflows on drainage basin slopes, and exposures of sedimentary succession were mapped and recorded. Extensive reconnaissance of the study area yielded qualitative data that was used in subsequent discussion.

On return to the laboratory, 170 sediment samples were analysed for grain-size characteristics, using a combined dry sieving/pipette technique. An experiment was also set up to assess the effect of freeze-thaw and organic breakdown in producing a clay-silt rich weathered fraction from fan sediments.

During field-work a study of fan morphology showed that active channels in the study area extend downfan approximately one-third of the distance between geometric apex and toe. Below the active apex the flow was observed spreading out into wide sheets of slow-moving water. As discharge decreased, these sheets were seen to subside into many separate flows, which persisted for the duration of field-work. This may account for the braided appearance of the fans, as noted in Plates 4 and 5. Individual fans are basically triangular in shape, with gentle slopes and concave-upwards profiles. Prominant lobes in the fanhead zones of Bear Creek and Tundra Creek fans separate two different levels or surfaces, and results of sediment analysis suggest that these may be due to mudflow activity.

A strong inverse statistical relationship exists between mean fan slope and drainage basin area, which agrees with similar results obtained from fans in California (Eckis, 1928; Bull, 1962a; Bull, 1964a) and Southern Arizona (Melton, 1965). This correlation suggests that larger catchment areas produce fans with gentler slopes. The larger the drainage basin, the greater will be the discharge from the mountain front and the greater will be the likelihood of a predominantly fluvial system producing gentler fan slopes (Leopold, Wolman, and Miller, 1964, p. 256).

Compared with other available data provided by Bull (1964c), there is little fanhead trenching in the study area, other than that of Slide Creek. The fanhead trenching that

was noted is probably due to erosion in the normal course of the cycle, as the Aklavik Range is worn back by the headward erosion of flanking streams. The absence of deep fanhead incision may be related to the input of sediment load by mountain slope mudflows, reducing the amount of energy available for erosion. The predominantly smooth, concave-upwards fan profiles, and the absence of deep fanhead trenching suggest that changes in base-level, or periods of mountain uplift are unlikely to have occurred since deglaciation.

Problems were encountered during analysis of the grain-size characteristics of study area sediments, due to the high percentage of clay and clay-silt present in the samples, creating cumulative curves of particle size distribution that were very open-ended. Descriptive statistics which use a wide range of percentiles, such as those suggested by Inman (1952) and Folk and Ward (1957) were therefore precluded, and the writer was forced to use less efficient methods such as a visual comparison of grain-size curves and calculation of Trask (1932) median and sorting coefficient statistics. These techniques showed that some similarity existed between the grain-size characteristics of fan and mountain mudflow samples, although the coarser fan sediments formed a separate grouping and may have been deposited by some other process.

Application of the Passega/Bull CM pattern model although unproven, suggested that fan samples can be classified into one of at least three groups--lateral accretion

deposits; mudflow deposits; and overbank deposits. The sample locations for these three groups were plotted and showed a grouping of mudflow samples around fan apices with overbank deposits relatively evenly distributed below the fanhead zone. Further evidence from exposures of sedimentary sequences and fan boreholes support the argument that mudflows deposit sediment in the fanhead zone, with lateral accretion by active channels near the fan apex and overbank flow depositing much of the sediment over the lower two-thirds of the fan surface.

Available climatic data for the Aklavik area suggests that such a multi-process hypothesis is possible and that the chief characteristic of the hydrologic regime is a spring flood, a conclusion supported by field observations. The flow produced by this 'freshet' could be highly fluid or viscous, dependent on the amount of sediment supplied by mountain mudflows and other forms of mass-wasting. The variability of the water:sediment ratio of the spring flood probably accounts for the presence of both mudflows and lateral accretion deposits in the fanhead zone. Vertical accretion of fine material would result from overbank discharge from the active channel, and from the spreading out of the unconfined flow below the active apex. These conclusions are supported by the analysis of fan morphology, insofar as the longitudinal profiles of Bear Creek and Tundra Creek fans indicate lobes, which may be due to mudflows, superimposed

on smooth, concave-upwards slopes, probably created by fluvial action.

Mudflows are a common feature of drainage basin slopes and are active in transporting clay-silt rich material from the upland tundra to the valley floors. Excessive mudflow activity may result in the temporary damming of creeks, and the ponding up of a considerable head of water. The breaching of such dams was noted in the field, and is a source of much of the clay-silt rich fan sediment. Laboratory experiments indicate that further comminution of fan sediment may take place after deposition, in response to a combination of freeze-thaw action and organic breakdown.

The results outlined above are by no means conclusive, but provide a process model for the present development of the Aklavik fans. It should be borne in mind that the samples collected and analysed were of surficial material, the presence of permafrost preventing the collection of sediment at depth. The study indicates that in terms of the samples taken, vertical accretion of overbank deposits accounts for the greatest amount of sediment depositon, but further research, possibly in the form of diamond-bit borings into the permafrost, is necessary to assess more accurately the proportions of mudflow, lateral accretion, and vertical accretion sediment. The most serious problem that occurred during analysis, was the inability to describe the study area sediments in a definite, quantitative way, due to

the open-ended nature of the grain-size curves. It is hoped that some technique will be developed whereby such sediments can be described in terms of mean, standard deviation, skewness and kurtosis, without causing the inaccuracies produced by curve extrapolation.

This study does show that it is possible to determine the nature and areal pattern of processes from static data such as morphology and sediment characteristics. However, such results should be interpreted with care, in the light of available literature and in relation to field observation.

BIBLIOGRAPHY

Apfel, E. T., 1939, "Phase sampling of sediments", _Jour. Sed. Petrol._, Vol. 8, pp. 67-68.

Beaty, C. B., 1963, "Origin of alluvial fans, White Mountains, California and Nevada", _Ann. Assoc. Am. Geog._, Vol. 53, pp. 516-535.

Bird, J. B., 1967, "_The physiography of Arctic Canada_", Baltimore, John Hopkins Press, 336 pp.

Black, R. F., 1954, "Permafrost - A review", _Bull. Geol. Soc. Am._, Vol. 65, pp. 839-856.

Blackwelder, E., 1928, "Mudflow as a geologic agent in semi-arid mountains", _Bull. Geol. Soc. Am._, Vol. 39, pp. 465-483.

________, 1931, "Desert Plains", _Jour. Geol._, Vol. 39, pp. 133-140.

Blissenbach, E., 1952, "Relation of surface angle distribution to particle size on alluvial fans", _Jour. Sed. Petrol._, Vol. 22, pp. 25-28.

________, 1954, "Geology of alluvial fans in semi-arid regions", _Bull. Geol. Soc. Am._, Vol. 65, pp. 175-190.

Bluck, B. J., 1964, "Sedimentation of an alluvial fan in Southern Nevada", _Jour. Sed. Petrol._, Vol. 34, pp. 395-400.

Brown, R. J. E., 1960, "The distribution of permafrost with relation to air temperature in Canada and the U.S.S.R.", _Arctic_, Vol. 13, pp. 163-177.

Bull, W. B., 1962a, "Relations of alluvial fan size and slope to drainage basin size and lithology in Western Fresno County, California", _U. S. Geol. Surv. Prof. Pap._, No. 450-B, Article 19, pp. 51-53.

________, 1962b, "Relations of textural (CM) patterns to depositional environment of alluvial fan deposits", _Jour. Sed. Petrol._, Vol. 32, pp. 211-215.

________, 1963, "Alluvial fan deposits in Western Fresno County, California", Jour. Geol., Vol. 71, pp. 243-251.

________, 1964a, "Alluvial fans and near-surface subsidence in Western Fresno County, California", U. S. Geol. Surv. Prof. Pap., No. 437-A, 71 pp.

________, 1964b, "Geomorphology of segmented alluvial fans in Western Fresno County, California", U. S. Geol. Surv. Prof. Pap., No. 352-E, 128 pp.

________, 1964c, "History and causes of channel trenching in Western Fresno County", Am. Jour. Sci., Vol. 262, pp. 249-258.

Buwalda, J. F., 1951, "Transportation of coarse material on alluvial fans", Bull. Geol. Soc. Am., (Abstract), Vol. 62, p. 1497.

Camsell, C., 1904, "Report on the Peel River and tributaries; Yukon and Mackenzie", Geol. Surv. Can. Ann. Rept., 1906, Vol. 16, part CC, pp. 1-49.

Chorley, R. J., 1962, "Geomorphology and general systems theory", U. S. Geol. Surv. Prof. Pap., No. 500-B, 10 pp.

Cook, F. A., 1967, "Fluvial processes in the High Arctic", Geog. Bull., Vol. 9(3), pp. 262-268.

Cooper, A. W., 1958, "Plant life-forms as indicators of microclimate". Unpublished Ph.D. Thesis, University of Michigan, 556 pp.

Corte, A. E., 1966, "Particle sorting by repeated freezing and thawing", Biul. Peryglac., Vol. 15, pp. 176-240.

Croft, A. R., 1962, "Some sedimentation phenomena along the Wasatch Mountain front", Jour. Geophys. Res., Vol. 67, pp. 1511-1524.

Czeppe, Z., 1965, "Activity of running water in southwest Spitzbergen", Geog. Polon., Vol. 6, pp. 141-150.

Denny, C. S., 1965, "Alluvial fans in the Death Valley region, California and Nevada", U. S. Geol. Surv. Prof. Pap., No. 466, 62 pp.

Eckis, R., 1928, "Alluvial fans in the Cucamonga District, Southern California", Jour. Geol., Vol. 36, pp. 224-247.

Fraser, J. K., 1956, "Physiographic notes on features in the Mackenzie Delta area", Can. Geog., No. 8, pp. 18-23.

________, 1959, "Freeze-thaw frequencies and mechanical weathering in Canada", Arctic, Vol. 12(1), pp. 40-53.

Folk, R. L., and W. C. Ward, 1957, "Brazos River bar: a study in the significance of grain-size parameters", Jour. Sed. Petrol., Vol. 27, pp. 3-26.

Freidman, G. M., 1961, "Distinction between dune, beach, and river sands from their textural characteristics", Jour. Sed. Petrol., Vol. 31, pp. 514-529.

________, 1967, "Dynamic processes and statistical parameters compared for size frequency distributions of beach and river sands", Jour. Sed. Petrol., Vol. 37, pp. 327-354.

Gabrielse, H., 1957, "Geological reconnaissance in the northern Richardson Mountains, Yukon and N.W.T.", Geol. Surv. Can. Pap., No. 56-6, 11 pp.

Greenwood, B., 1969, "Sediment parameters and environment discrimination; an application of multivariate statistics", Can. Jour. Earth Sci., Vol. 6(6), pp. 1347-1358.

Griffiths, J. C., 1967, "Scientific method in analysis of sediments", New York, McGraw-Hill, 508 pp.

Harris, S. A., 1958, "Differentiation of various Egyptian eolian microenvironments by mechanical composition", Jour. Sed. Petrol., Vol. 28, pp. 164-174.

Henoch, W. E. S., 1960, "Geographical Branch survey in the Mackenzie Delta and Peel River area, 1958", Arctic Circular, Vol. 13(1), pp. 9-15.

Hooke, R. LeB., 1967, "Processes on arid-region alluvial fans", Jour. Geol., Vol. 75, pp. 438-460.

Hope, K., 1967, "Elementary statistics", Oxford, Pergamon Press, 101 pp.

Hoppe, G., and S. R. Ekman, 1964, "A note on the alluvial fans of Ladtjovarre, Swedish Lapland", Geog. Ann., Vol. 46, pp. 338-342.

Inman, D. L., 1952, "Measures for describing the size distribution of sediments", Jour. Sed. Petrol, Vol. 22, pp. 125-145.

Jeletzky, J. A., 1958, "Uppermost Jurassic and Cretaceous rocks of the Aklavik Range, northeastern Richardson Mountains, N.W.T.", Geol. Surv. Can. Pap., No. 58-2, 84 pp.

________, 1961, "Eastern slope, Richardson Mountains; Cretaceous and Tertiary structural history and regional significance", Proc. of Internat. Symposium on Arctic Geology, 1961, Vol. 1, pp. 532-583.

Keeble, A. B., 1971, "Freeze-thaw cycles and rock weathering in Alberta", Albertan Geographer, No. 7, (in press).

Kerfoot, D. E., 1969, "The geomorphology and permafrost conditions of Garry Island, N.W.T.", Unpublished Ph.D. Thesis, University of British Columbia.

Kesseli, J. E., and C. B. Beaty, 1959, "Desert flood conditions in the White Mountains of California and Nevada", U. S. Army Quartermaster Research and Engineering Command Tech. Rept., EP-108, 107 pp.

King, C. A. M., 1966, "Techniques in Geomorphology", London, Edward Arnold, 342 pp.

Klovan, J. E., 1966, "The use of factor analysis in depositional environments from grain-size distributions", Jour. Sed. Petrol., Vol. 36, pp. 115-125.

Kononova, M., 1966, "Soil organic matter; its nature, its role in soil formation and in soil fertility", Oxford, Pergamon Press, 544 pp.

Krumbein, W. C., 1936, "Application of logarithmic moments in size frequency distributions of sediments", Jour. Sed. Petrol., Vol. 6, pp. 35-47.

________, 1937, "Sediments and exponential curves", Jour. Geol., Vol. 45, pp. 577-601.

________, and F. J. Pettijohn, 1938, "Manual of sedimentary petrography", New York, Appleton-Century-Crofts Inc., 549 pp.

Lambert, J. D. H., 1968, "The ecology and successional trends of tundra plant communities in the low Arctic subalpine zone of the Richardson and British Mountains of the Canadian Western Arctic", Unpublished Ph.D. Thesis, University of British Columbia.

Landim, P. M. B., and L. A. Frakes, 1968, "Distinction between tills and other diamictons based on textural characteristics", Jour. Sed. Petrol., Vol. 38, pp. 1213-1223.

Leahey, A., 1947, "Characteristics of soils adjacent to the Mackenzie River in the N.W.T. of Canada", Proc. Am. Soil. Sci. Soc., Vol. 12, pp. 458-461.

Leggett, R. F., and R. J. E. Brown, 1956, "Rapid disintegration of alluvial fan material near Aklavik, N.W.T.", Bull. Geol. Soc. Am., Vol. 67, p. 1715.

________, ________, and G. H. Johnston, 1966, "Alluvial fan formation near Aklavik, N.W.T.", Bull. Geol. Soc. Am., Vol. 77, pp. 15-30.

Leopold, L. B., M. G. Wolman, and J. P. Miller, 1964, "Fluvial processes in geomorphology", San Francisco, W. H. Freeman and Co., 522 pp.

Longwell, C. R., 1930, "Faulted fans west of the Sheep Range, south Nevada", Am. Jour. Sci., Vol. 20, pp. 1-13.

Lustig, L. K., 1965, "Clastic sedimentation in Deep Springs Valley, California", U. S. Geol. Surv. Prof. Pap., No. 352-F, 192 pp.

Mackay, J. R., 1957, "Notes on small boat harbours, N.W.T.", Canada; Dept. Mines, and Tech. Surv; Geog. Branch; Geog. Pap., No. 13, 11 pp.

________, 1958, "A subsurface organic layer associated with permafrost in the Western Arctic", Canada; Dept. Mines and Tech. Surv; Geog. Branch; Geog. Pap., No. 18, 21 pp.

________, 1963, "The Mackenzie Delta, N.W.T.", Canada; Dept. Mines and Tech. Surv; Geog. Branch; Mem., No. 8, 202 pp.

Martin, L. J., 1961, "Tectonic framework of Northern Canada", Proc. of Internat. Symposium on Arctic Geology, 1961, Vol. 1, pp. 442-457.

Mason, C. C., and R. L. Folk, 1958, "Differentiation of beach, dune, and eolian flat environments by size analysis, Mustang Island, Texas", Jour. Sed. Petrol., Vol. 28, pp. 211-226.

Melton, M. A., 1965, "The geomorphic and paleaoclimatic significance of alluvial fan deposits in southern Arizona", Jour. Geol., Vol. 73, pp. 1-38.

Murata, T., 1966, "A theoretical study of the forms of alluvial fans", Tokyo Metropolitan Univ. Geog. Rept., Vol. 1, pp. 33-43.

Passega, R., 1957, "Texture as a characteristic of clastic deposition", Bull. Am. Assoc. Petrol. Geol., Vol. 41, pp. 1952-1984.

________, 1964, "Grain-size representation by CM patterns as a geological tool", Jour. Sed. Petrol., Vol. 34, pp. 830-847.

Pihlainen, J. A., R. J. E. Brown, and G. H. Johnston, 1956, "Soils in some areas of the Mackenzie River Delta region", Natl. Res. Counc. Can. Building Res. Tech. Pap., No. 43(NRC 4096) 26 pp.

Potts, A. S., 1970, "Frost action in rocks; some experimental data", Trans. Inst. Brit. Geog., Vol. 49, pp. 109-124.

Prior, D. B., N. Stephens, and D. R. Archer, 1968, "Composite mudflows on the Antrim coast of north-east Ireland", Geog. Ann., Vol. 50, Ser. A, pp. 65-78.

Raiche, P., 1950, "A survey of weathering processes and products", Albuquerque, Univ. of New Mexico Press, Revised Ed., 95 pp.

Rudberg, S., 1963, "Geomorphological processes in a cold, semi-arid, region", Axel Heiberg Prelim. Rept., 1961-1962, (by F. Müller and others) McGill Univ., Montreal, pp. 139-150.

Ruhe, R. W., 1964, "Landscape morphology and alluvial deposits in southern New Mexico", Ann. Assoc. Am. Geog., Vol. 54, pp. 147-159.

Sahu, B. K., 1964, "Depositional mechanisms from the size analysis of clastic sediments", Jour. Sed. Petrol., Vol. 34, pp. 73-83.

Sevon, W. D., 1966, "Distinction of New Zealand beach, dune and river sands by their grain-size distribution characteristics", N. Z. Jour. Geol. and Geophys., Vol. 9, pp. 212-223.

Sharpe, C. F. S., 1938, "Landslides and related phenomena", New Jersey, Pageant Book Inc., 271 pp.

Sharp, R. P., 1942, "Soil structures in the St. Elias Range, Yukon Territory", Jour. Geomorph., Vol. 5, pp. 274-301.

________, and L. H. Nobles, 1953, "Mudflow of 1941 at Wrightwood, southern California", Bull. Geol. Soc. Am., Vol. 64, pp. 547-560.

Sigafoos, R. S., and D. M. Hopkins, 1952, "Soil instability on slopes in regions of permanently frozen ground", in "Frost action in soils; a symposium", Washington, D.C., Highway Research Board, pp. 176-192.

Sölch, J., 1949, "Uber die schwemmkegel der Alpen", Geog. Ann., Vol. 31, pp. 369-383.

Spitz, O. T., M. O'Leary, and R. H. Lippert, 1964, "Fortran IV and map program for computation and plotting of trend surfaces for degrees 1 through 6", Univ. of Kansas Computational Centre Pub.

Trask, P. D., 1932, "Origin and environment of source sediments of petroleum", Houston, Texas, Gulf Pub. Co., 323 pp.

Tricart, J., 1956, "Étude expérimentale du problème de la gélivation", Biul. Peryglac., No. 4.

Wentworth, C. K., 1929, "Method of computing mechanical composition of types of sediments", Bull. Geol. Soc. Am., Vol. 40, pp. 771-790.

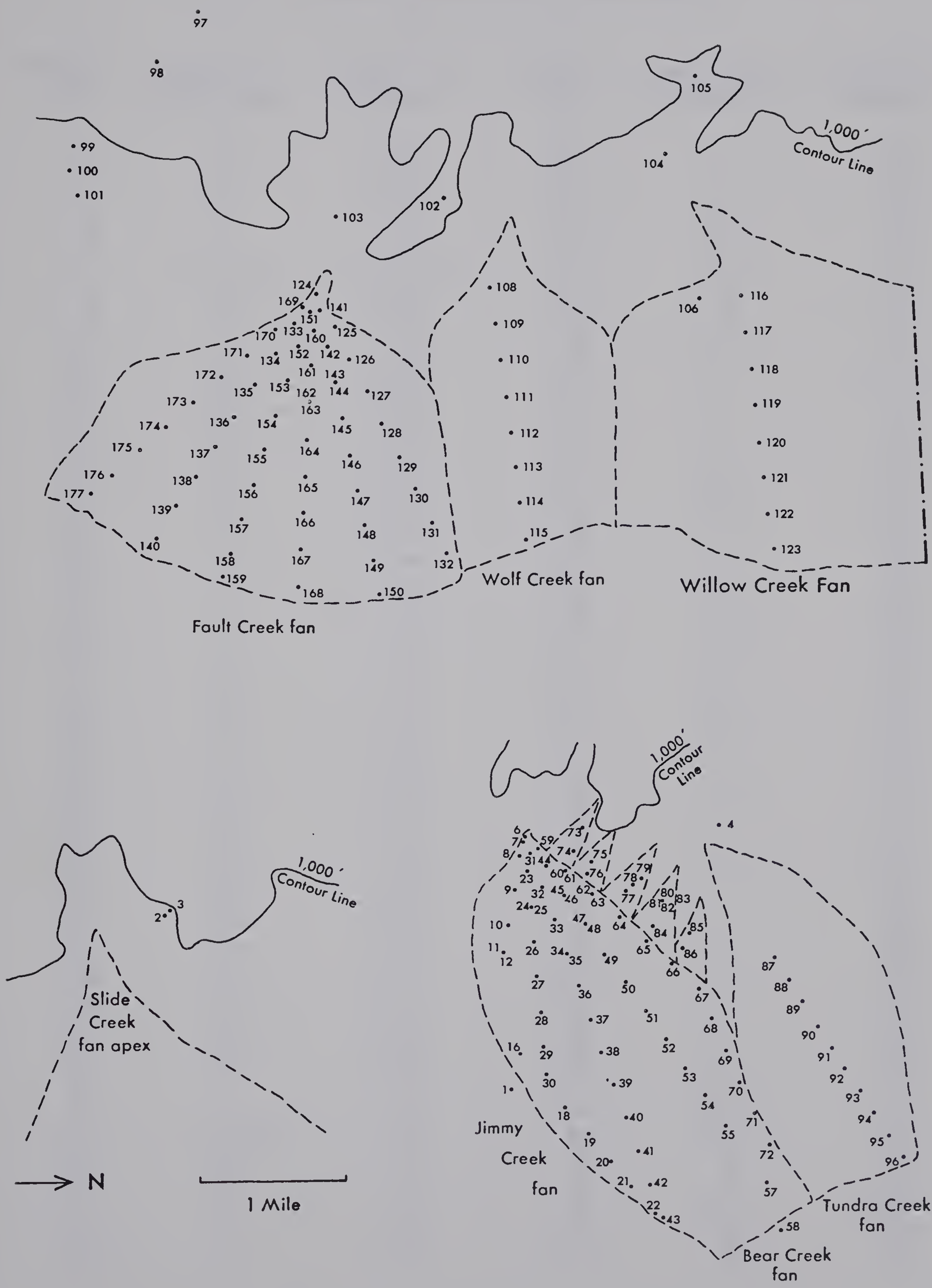
Williams, J. R., 1963, "Geologic reconnaissance of the Yukon Flats Cenozoic basin, Alaska", U. S. Geol. Surv. Bull., No. 1111-H, pp. 289-331.

Wiman, S., 1963, "A preliminary study of experimental frost weathering", Geog. Ann., Vol. 45, pp. 113-121.

Winder, C. G., 1965, "Alluvial cone construction by an alpine mudflow in a humid temperate region", Can. Jour. Earth Sci., Vol. 2, pp. 270-277.

Yatsu, E., 1959, "On the discontinuity of grain-size frequency distributions of fluvial deposits and its geomorphological significance", Internat. Geog. Union, Regional Conf. Japan, Proc, 1957, pp. 224-242.

APPENDIX A Sample Locations



APPENDIX B SAMPLE AND PERMAFROST DEPTHS

N.B:- ? denotes data not available

Sample No.	Depth to Permafrost	Depth to Sample	Sample No.	Depth to Permafrost	Depth to Sample
1	?	1"	50	?	6"
2	?	15"	51	?	6"
3	?	29"	52	?	6"
4	?	12"	53	12"	9"
6	?	1"	54	6"	10"
7	10-1/2"	11-1/2"	55	6"	11"
8	8"	10"	57	5"	11"
9	6"	5"	58	?	6"
10	7"	8"	59	7"	14"
11	22"	24"	60	?	3-1/2"
12	24"	20"	61	?	8"
16	6"	9"	62	?	3"
18	6"	11"	63	?	10"
19	5"	8"	64	10"	15"
20	?	1/2"	65	8"	13"
21	?	1"	66	?	10"
22	?	9"	67	?	6"
23	5"	11"	68	13"	14"
24	?	5"	69	6"	10"
25	?	9"	70	7"	12"
26	5"	9"	71	5"	9"
27	5"	9"	72	?	16"
28	5"	11"	73	10"	11"
29	7"	11"	74	?	19"
30	9"	11"	75	8"	11"
31	8"	12"	76	9"	11"
32	10"	12"	77	?	11"
33	6"	16"	78	?	1/2"
34	12"	8"	79	?	14"
35	12"	13"	80	?	16"
36	7"	13"	81	?	32"
37	10"	11"	82	?	30"
38	7"	11"	83	?	48"
39	8"	13"	84	9"	16"
40	8"	12"	85	?	18"
41	6"	12"	86	?	16"
42	?	10"	87	9"	11"
43	?	9"	88	14"	13"
44	6-1/2"	14"	89	10"	16"
45	11"	6"	90	9"	14"
46	11"	12"	91	7"	10"
47	?	5"	92	14"	13"
48	?	10"	93	9"	13"
49	?	1"	94	7"	11"

Sample No.	Depth to Permafrost	Depth to Sample	Sample No.	Depth to Permafrost	Depth to Sample
95	8"	12"	137	?	13"
96	11"	14"	138	?	15"
97	?	12"	139	9"	12"
98	?	14"	140	13"	17"
99	?	4"	141	9"	11"
100	?	21"	142	?	13"
101	?	3"	143	?	1"
102	?	1"	144	?	4"
103	?	11"	145	?	9"
104	?	3"	146	?	4"
105	?	7"	147	10"	13"
106	?	13"	148	?	19"
108	7"	11"	149	13"	16"
109	8"	13"	150	14"	13"
110	8"	12"	151	?	
111	10"	12"	152	?	12"
112	12"	14"	153	?	12"
113	9"	12"	154	10"	12"
114	8"	11"	155	10"	12"
115	11"	14"	156	10"	13"
116	8"	11"	157	?	12"
117	?	18"	158	9"	14"
118	13"	10"	159	8"	14"
119	8"	10"	160	14"	17"
120	11"	13"	161	?	15"
121	?	14"	162	15"	18"
122	?	17"	163	15"	14"
123	15"	12"	164	?	8"
124	10"	12"	165	?	12"
125	?	18"	166	11"	15"
126	14"	16"	167	?	13"
127	15"	14"	168	?	12"
128	?	11"	169	12"	14"
129	9"	12"	170	?	12"
130	7"	18"	171	9"	12"
131	10"	15"	172	?	11"
132	11"	15"	173	18"	15"
133	?	16"	174	?	11"
134	9"	14"	175	?	14"
135	10"	13"	176	9"	13"
136	8"	11"	177	?	10"

APPENDIX C SAMPLE STATISTICS--MEDIAN AND TRASK SORTING COEFFICIENT

Sample No.	Median	Trask Sorting Coefficient
1	1.84037	1.61838
2	0.03874	4.00000
3	1.97246	1.87904
4	0.02210	4.33190
6	0.37702	1.62276
7	0.02062	3.54307
8	0.02120	2.81864
9	0.00962	3.62378
10	0.01563	3.31728
11	2.21161	1.83948
12	0.00576	4.36203
16	0.01045	3.00008
18	0.00501	4.39237
19	0.00194	2.94854
20	0.04036	1.63535
21	0.01620	2.15845
22	0.03169	1.91189
23	0.01113	4.24275
24	3.12618	2.91208
25	0.00904	3.98616
26	0.00592	3.39874
27	0.00159	3.87716
28	0.01795	3.03143
29	0.02385	2.41999
30	0.02628	4.14106
31	0.01031	3.89062
32	0.28919	3.63423
33	0.01734	4.40762
34	0.02005	4.39237
35	0.02179	5.65685
36	0.00367	3.66802
37	0.00580	3.43426
38	0.00232	3.51860
39	0.00198	6.10503
40	0.00781	3.00008
41	0.00501	3.39874
42	0.01588	2.12182
43	0.03202	1.87989
44	0.01509	3.74509
45	2.14414	2.42536
46	0.01184	3.55537
47	1.21521	2.52485
48	0.01105	2.81864
49	0.01105	2.62079
50	0.00138	3.47015
51	0.01269	2.73208
52	0.00364	5.40765
53	0.00148	2.80889
54	0.00138	5.65634
55	0.00127	4.53154
57	0.00364	4.74037
58	1.18198	5.92206
59	0.00391	5.27803
60	1.88923	2.62178
61	0.03492	3.35195
62	0.01563	3.05252
63	1.58173	1.96183
64	0.01031	4.67511
65	0.03349	2.95877
66	0.01314	2.37841
67	0.03019	2.37019
68	0.00209	3.59253
69	0.01595	2.71321
70	0.02210	2.37842
71	0.00508	5.01065
72	0.00481	4.48466
73	0.01795	6.72716
74	0.00929	7.56846
75	0.02720	9.84916
76	0.01524	6.72717
77	0.02816	5.85635
78	0.51559	3.27739
79	0.02628	5.65686
80	0.00652	3.58010
81	2.62497	3.12737
82	0.01924	3.24901
83	0.01269	5.15153
84	0.02241	4.72397
85	0.10882	28.34450
86	0.04269	2.71321

87	0.62417	2.10672	133	0.03235	16.56424
88	2.38204	2.15397	134	0.01563	7.01284
89	0.01031	6.27667	135	0.01314	5.46416
90	0.00436	3.97237	136	0.01438	5.52127
91	0.02876	4.14106	137	2.82843	1.79005
92	2.56632	2.41806	138	0.01031	3.19320
93	0.03019	3.79737	139	0.02610	2.65737
94	0.00153	4.56305	140	0.01618	6.58873
95	0.01144	2.82843	141	0.02210	7.11074
96	0.00328	4.59479	142	2.84297	2.32269
97	0.01226	7.43844	143	1.46145	1.66902
98	0.00962	6.72717	144	0.02664	2.80889
99	0.00465	7.54227	145	0.01031	3.86374
100	0.01332	5.55967	146	2.26624	1.89395
101	0.00335	4.45368	147	0.00584	3.93128
102	0.02062	5.38893	148	0.00171	4.12673
103	0.09473	14.12322	149	0.00515	5.55967
104	3.11514	3.34255	150	0.00552	4.92458
105	0.01458	4.67511	151	3.43426	2.94854
106	0.13260	1.60531	152	0.22995	2.86245
108	0.00781	7.59473	153	5.54581	2.19687
109	0.00657	6.84476	154	0.02876	6.06287
110	0.00781	5.20537	155	0.02401	3.55537
111	0.02646	4.12673	156	0.02062	4.19887
112	0.01618	2.81864	157	0.03467	4.00000
113	0.01795	4.43828	158	0.00185	4.43828
114	0.00138	4.78991	159	0.00377	3.66802
115	0.00028	5.85634	160	1.30134	2.74156
116	3.18325	3.99418	161	0.03125	3.44618
117	1.34341	3.34406	162	0.02368	4.28709
118	0.01489	6.63456	163	0.01448	6.61160
119	0.00897	4.75683	164	1.31522	2.01021
120	1.14870	2.23457	165	0.01458	4.51586
121	1.59693	3.07439	166	0.01067	4.06992
122	0.01269	6.23332	167	1.27456	3.30580
123	0.00820	3.13834	168	0.00148	4.16986
124	1.05709	4.19450	169	0.01458	5.50217
125	0.02033	5.33319	170	0.07695	36.88589
126	0.00290	4.14106	171	0.01438	4.00000
127	0.02134	4.99332	172	2.88346	1.95301
128	0.00170	6.19026	173	0.00416	3.49429
129	0.00105	2.86791	174	0.00227	3.79737
130	0.00180	4.37717	175	0.00240	3.81055
131	0.00066	3.66802	176	0.00227	3.73213
132	0.00049	4.97604	177	0.00393	4.70762

APPENDIX D

SAMPLE STATISTICS-PERCENTAGE WEIGHT OF GRAIN-SIZE CLASSES

SAMPLE NO.	SLOPE (FEET/ 000 FEET)	DISTANCE FROM APEX (FEET)	GRAIN-SIZE INDICES AS PERCENTAGES OF SAMPLE WEIGHTS CLAY %	SILT %	CLAY-SILT %	SAND %	GRAVEL %	SANO-GRAVEL %
1	0.0	0.0	0.0	0.0	8.4181	46.0582	45.5237	91.5819
2	0.0	0.0	10.8380	54.1898	65.0278	14.2052	20.7670	34.9722
3	0.0	0.0	0.0	0.0	6.6691	44.7162	48.6147	93.3309
4	0.0	0.0	22.1831	57.6280	79.8111	18.6748	1.5141	20.1889
6	97.0	0.0	0.0	0.0	2.8954	96.7453	0.3593	97.1046
7	90.0	150.0	15.0992	60.3966	75.4958	24.5042	0.0	24.5042
8	87.0	500.0	13.5484	67.0967	80.6451	19.3549	0.0	19.3549
9	87.0	1500.0	23.8299	66.5440	90.3739	9.6261	0.0	9.6261
10	58.0	2500.0	19.1048	73.6901	92.7949	7.2051	0.0	7.2051
11	35.0	3250.0	0.0	0.0	1.4943	44.0326	54.4731	98.5057
12	35.0	3250.0	33.1338	59.4592	92.5930	6.3045	1.1025	7.4070
16	31.5	6100.0	21.2615	75.9340	97.1955	2.8045	0.0	2.8045
18	34.0	7730.0	29.7418	53.3413	83.0831	9.3653	7.5516	16.9169
19	18.0	8630.0	49.8543	49.2069	99.0612	0.9388	0.0	0.9388
20	14.0	9500.0	3.6999	68.6154	72.3153	27.6847	0.0	27.6847
21	12.0	10380.0	8.9973	87.4740	96.4713	3.5287	0.0	3.5287
22	9.5	11300.0	6.9646	71.3873	78.3519	21.6481	0.0	21.6481
23	76.0	1000.0	25.3437	62.7257	88.0694	11.9306	0.0	11.9306
24	81.0	2000.0	0.0	0.0	3.2486	36.5595	60.1919	96.7514
25	81.0	2000.0	24.0964	61.1677	85.2641	6.4133	8.3226	14.7359
26	69.5	3000.0	30.7183	66.9659	97.6842	2.3158	0.0	2.3158
27	48.5	4000.0	53.9478	42.3460	96.2938	2.7089	0.9973	3.7062
28	47.0	5000.0	16.1334	73.1383	89.2717	10.7283	0.0	10.7283
29	31.5	6000.0	11.9196	82.4007	94.3203	5.6797	0.0	5.6797
30	27.0	6750.0	20.6044	56.3187	76.9231	22.8983	0.1786	23.0769
31	87.0	500.0	18.5060	67.2948	85.8008	12.9374	1.2618	14.1992
32	74.0	1500.0	2.2183	13.3101	15.5284	66.0142	18.4574	84.4716
33	60.0	2500.0	15.6809	57.3335	73.0144	20.2970	6.6886	26.9856
34	39.0	3500.0	23.6227	64.0100	87.6327	11.8266	0.5407	12.3673
35	39.0	3500.0	25.8449	53.6282	79.4731	16.4599	4.0670	20.5269
36	33.0	4500.0	39.4108	59.1162	98.5270	1.4730	0.0	1.4730
37	29.0	5500.0	30.4219	67.4299	97.8518	2.1482	0.0	2.1482
38	28.0	6500.0	47.3010	49.7393	97.0403	2.9597	0.0	2.9597
39	23.0	7500.0	50.0632	48.1523	98.2155	1.7845	0.0	1.7845
40	18.0	8500.0	21.8551	69.9361	91.7912	7.8416	0.3672	8.2088
41	14.0	9500.0	33.2787	65.5642	98.8429	1.1571	0.0	1.1571
42	11.0	10500.0	2.1695	95.1865	97.3560	2.6440	0.0	2.6440
43	9.0	11500.0	1.4772	79.7671	81.2443	18.7557	0.0	18.7557
44	76.0	1000.0	20.5603	65.7196	86.2799	13.7201	0.0	13.7201
45	81.0	2000.0	0.0	0.0	2.8253	45.0399	52.1348	97.1747
46	81.0	2000.0	21.5018	63.2152	84.7170	14.7716	0.5114	15.2830
47	69.5	3000.0	1.6300	7.7211	9.3511	59.5785	31.0704	90.6489
48	69.5	3000.0	21.3131	75.6408	96.9539	2.8542	0.1919	3.0461
49	48.5	4000.0	11.0902	87.8690	98.9592	1.0408	0.0	1.0408
50	47.0	5000.0	58.3800	41.3524	99.7324	0.2676	0.0	0.2676
51	31.5	6000.0	17.6859	80.0522	97.7381	2.2619	0.0	2.2619
52	24.5	7000.0	43.9517	55.9384	99.8901	0.1099	0.0	0.1099
53	22.0	8000.0	56.6194	43.2365	99.8559	0.1441	0.0	0.1441
54	14.5	9000.0	53.6509	45.7995	99.4504	0.5496	0.0	0.5496
55	12.5	10000.0	56.3834	41.6163	97.9997	2.0003	0.0	2.0003
57	15.0	12000.0	41.0654	53.9715	95.0369	4.9631	0.0	4.9631
58	0.0	0.0	1.2614	18.3807	19.6421	44.8335	35.5244	80.3579
59	87.0	500.0	37.2077	56.6973	93.9050	6.0950	0.0	6.0950
60	74.0	1500.0	0.0	0.0	1.4356	49.8667	48.6975	98.5642
61	74.0	1500.0	9.7520	54.3327	64.0847	35.6645	0.2508	35.9153
62	60.0	2500.0	17.2226	71.6099	88.8325	11.1675	0.0	11.1675
63	60.0	2500.0	1.6233	9.7401	11.3634	47.8763	40.7603	88.6366
64	39.0	3500.0	26.5399	59.7146	86.2545	9.0346	4.7109	13.7455
65	33.0	4500.0	14.5810	56.6086	71.1896	28.8104	0.0	28.8104
66	29.0	5500.0	14.7215	80.9683	95.6898	4.3102	0.0	4.3102
67	28.0	6500.0	12.6486	67.4592	80.1079	19.8921	0.0	19.8921
68	24.0	7400.0	48.4305	51.1211	99.5516	0.4484	0.0	0.4484
69	19.0	8350.0	18.4259	71.9487	90.3746	9.6254	0.0	9.6254
70	13.0	9280.0	14.2504	80.7524	95.0028	4.9972	0.0	4.9972
71	13.0	10200.0	38.6823	61.1430	99.8253	0.1747	0.0	0.1747
72	9.5	11180.0	38.8720	59.6890	97.5610	2.4390	0.0	2.4390
73	0.0	0.0	27.6120	50.7705	78.3825	13.6813	7.9362	21.6175
74	0.0	0.0	34.0587	49.1958	83.2545	12.8949	3.8506	16.7455
75	0.0	0.0	25.9885	38.0549	64.0430	13.2449	22.7121	35.9570
76	0.0	0.0	28.4112	47.8505	76.2617	14.5719	9.1664	23.7383
77	0.0	0.0	24.1687	42.4784	66.6471	20.3823	12.9706	33.3529
78	0.0	0.0	3.7954	10.1211	13.9165	69.7332	16.3503	86.0835
79	0.0	0.0	22.5748	46.9798	69.5546	20.7810	9.6644	30.4454
80	0.0	0.0	30.7980	60.6626	91.4606	8.3434	0.1960	8.5394
81	0.0	0.0	2.2769	7.7417	10.0186	34.4552	55.5262	89.9814
82	0.0	0.0	20.3087	69.8619	90.1706	8.8545	0.9749	9.8294
83	0.0	0.0	28.8210	60.2619	89.0829	10.6725	0.2446	10.9171
84	0.0	0.0	22.8242	53.5874	76.4116	18.7555	4.8329	23.5884
85	0.0	0.0	8.6029	27.9594	36.5623	17.5197	45.9180	63.4377
86	0.0	0.0	12.9460	50.1659	63.1119	29.1043	7.7838	36.8881
87	62.0	0.0	0.0	0.0	7.4331	85.9112	6.6557	92.5669
88	70.0	750.0	0.0	0.0	3.1729	40.6914	56.1357	96.8271
89	59.0	1500.0	26.9663	47.6404	74.6067	25.3933	0.0	25.3933

90	43.0	2250.0	38.0307	60.6434	98.6741	1.3259	0.0	1.3259
91	39.0	3000.0	16.6543	52.7387	69.3930	24.8982	5.7088	30.6070
92	31.0	3750.0	2.0087	8.0346	10.0433	32.3738	57.5829	89.9567
93	24.0	4500.0	13.6763	56.2833	69.9596	24.9751	5.0653	30.0404
94	20.0	5250.0	54.9199	44.6224	99.5423	0.4577	0.0	0.4577
95	21.0	6000.0	22.0070	73.7236	95.7306	4.2694	0.0	4.2694
96	16.0	6750.0	41.7412	55.6549	97.3961	2.6039	0.0	2.6039
97	0.0	0.0	33.1747	43.9924	77.1671	16.6306	6.2023	22.8329
98	0.0	0.0	34.3495	46.5149	80.8644	15.3714	3.7642	19.1356
99	0.0	0.0	39.3701	42.3228	81.6929	4.9015	13.4056	18.3071
100	0.0	0.0	27.9104	50.6794	78.5898	8.0352	13.3750	21.4102
101	0.0	0.0	40.7846	56.3216	97.1062	2.8938	0.0	2.8938
102	0.0	0.0	25.6937	52.2439	77.9376	20.7691	1.2933	22.0624
103	0.0	0.0	10.7391	23.3959	34.1350	33.1876	32.6774	65.8650
104	0.0	0.0	0.7862	3.3841	4.6343	35.4062	59.9595	95.3657
105	0.0	0.0	26.8632	52.1912	79.0544	11.2058	9.7398	20.9456
106	0.0	0.0	1.9279	14.6202	16.5481	82.5485	0.9034	83.4519
108	45.0	1200.0	35.3403	52.3560	87.6963	11.8586	0.4451	12.3037
109	40.0	2200.0	36.7610	53.0991	89.8601	10.1399	0.0	10.1399
110	35.0	3200.0	31.9781	64.8697	96.8478	3.1522	0.0	3.1522
111	30.0	4200.0	20.2752	53.5843	73.8595	13.3526	12.7879	26.1405
112	25.0	5200.0	21.1470	75.2834	96.4304	3.5696	0.0	3.5696
113	19.0	6200.0	26.2139	73.5127	99.7266	0.2734	0.0	0.2734
114	16.0	7200.0	55.5670	44.2478	99.8148	0.1852	0.0	0.1852
115	14.0	8200.0	77.1024	22.4135	99.5159	0.4841	0.0	0.4841
116	46.0	0.0	1.5974	6.2377	7.8351	32.7382	59.4267	92.1649
117	34.0	1000.0	1.5203	7.6017	9.1220	53.0506	37.8274	90.8780
118	28.0	2000.0	28.0161	60.4097	88.4258	11.5742	0.0	11.5742
119	23.0	3000.0	30.5266	67.4128	97.9394	2.0606	0.0	2.0606
120	22.0	4000.0	0.0	0.0	8.1841	61.9679	29.8480	91.8159
121	21.0	5000.0	1.7910	5.6845	7.4755	48.6483	43.8762	92.5245
122	12.0	6000.0	30.6538	50.1009	80.7597	17.9466	1.2937	19.2403
123	8.0	7000.0	25.8645	73.6577	99.5222	0.4778	0.0	0.4778
124	54.0	0.0	3.5421	9.3543	12.8934	51.9566	35.1500	87.1066
125	48.0	1000.0	28.4876	51.7955	80.2831	13.3719	6.3450	19.7169
126	49.0	2000.0	45.1495	50.0305	95.1800	4.6980	0.1220	4.8200
127	35.0	3000.0	23.1548	54.2692	77.4240	18.8929	3.6831	22.5760
128	25.0	4000.0	51.9129	47.3987	99.3116	0.6884	0.0	0.6884
129	22.0	5000.0	66.0024	33.6482	99.6506	0.3494	0.0	0.3494
130	17.0	6000.0	53.9648	45.1541	99.1189	0.8811	0.0	0.8811
131	16.0	7000.0	70.1009	29.7398	99.8407	0.1593	0.0	0.1593
132	14.0	8000.0	71.1141	28.2199	99.3340	0.6660	0.0	0.6660
133	40.0	1000.0	22.2014	36.5090	58.7104	17.4651	23.8245	41.2896
134	39.0	2000.0	29.0501	41.6383	70.6884	28.8855	0.4261	29.3116
135	31.0	3000.0	28.8511	47.3982	76.2493	23.7507	0.0	23.7507
136	27.0	4000.0	26.2713	51.6044	77.8757	22.1243	0.0	22.1243
137	24.0	5000.0	0.0	0.0	6.7802	29.7015	63.5183	93.2198
138	19.0	6000.0	29.3061	64.2844	93.5905	6.0030	0.4065	6.4095
139	21.0	7000.0	18.7318	70.2445	88.9763	11.0237	0.0	11.0237
140	13.0	8000.0	26.8764	43.9200	70.7964	28.9085	0.2951	29.2036
141	47.0	500.0	25.1485	41.2154	66.3639	22.5707	11.0654	33.6361
142	49.0	1500.0	0.0	0.0	0.6906	38.7496	60.5598	99.3094
143	43.0	2500.0	0.0	0.0	1.8301	64.8126	33.3573	98.1699
144	43.0	2500.0	15.0773	64.0784	79.1557	20.8443	0.0	20.8443
145	29.0	3500.0	25.8421	68.6152	94.4573	5.5427	0.0	5.5427
146	22.0	4500.0	0.0	0.0	4.5348	39.7612	55.7040	95.4652
147	22.0	5500.0	33.6587	65.0735	98.7322	1.2678	0.0	1.2678
148	16.0	6500.0	53.6535	42.5822	96.2357	3.7643	0.0	3.7643
149	14.0	7500.0	39.2562	51.6529	90.9091	9.0909	0.0	9.0909
150	13.0	8500.0	37.3703	60.8996	98.2699	1.7301	0.0	1.7301
151	43.0	500.0	0.0	0.0	5.2573	32.0366	62.7061	94.7427
152	38.0	1500.0	1.6484	11.9512	13.5996	69.7252	16.6752	86.4004
153	35.5	2500.0	0.0	0.0	2.4635	17.9903	79.5462	97.5365
154	30.5	3500.0	24.8608	41.7661	66.6269	22.6332	10.7399	33.3731
155	25.0	4500.0	20.1557	59.5511	79.7068	20.2932	0.0	20.2932
156	20.5	5500.0	21.5071	55.7591	77.2662	22.6541	0.0797	22.7338
157	19.5	6500.0	18.7291	46.1538	64.8829	34.2474	0.8697	35.1171
158	19.0	7500.0	52.9801	46.7991	99.7792	0.2208	0.0	0.2208
159	14.0	8500.0	39.7004	59.5507	99.2511	0.7489	0.0	0.7489
160	40.0	1000.0	0.0	0.0	5.8005	61.5205	32.6790	94.1995
161	39.0	2000.0	16.6647	53.5650	70.2297	29.4251	0.3452	29.7703
162	31.0	3000.0	23.0087	55.8781	78.8868	9.9156	11.1976	21.1132
163	31.0	3000.0	26.6864	44.4774	71.1638	18.5767	10.2595	28.8362
164	27.0	4000.0	0.0	0.0	4.0500	65.3158	30.6342	95.9500
165	24.0	5000.0	24.4862	56.4250	80.9113	19.0887	0.0	19.0887
166	19.0	6000.0	26.8562	66.3507	93.2069	6.7931	0.0	6.7931
167	21.0	7000.0	0.0	0.0	7.3617	54.7636	37.8747	92.6383
168	13.0	8000.0	58.5652	41.3400	99.9052	0.0948	0.0	0.0948
169	43.0	500.0	28.4210	45.9750	74.3960	24.7764	0.8276	25.6040
170	38.0	1500.0	16.6449	30.3951	47.0400	19.7496	33.2104	52.9600
171	35.5	2500.0	25.4545	60.9091	86.3636	13.6364	0.0	13.6364
172	30.5	3500.0	0.0	0.0	4.1572	32.0458	63.7970	95.8428
173	25.0	4500.0	39.7683	57.0588	96.8271	3.1729	0.0	3.1729
174	20.5	5500.0	48.8027	47.6676	96.4703	3.5297	0.0	3.5297
175	19.5	6500.0	47.3832	51.6907	99.0739	0.9261	0.0	0.9261
176	19.0	7500.0	48.1793	48.1792	96.3585	3.6415	0.0	3.6415
177	14.0	8250.0	40.5470	54.8576	95.4046	4.5954	0.0	4.5954